FINAL REPORT

UNDERWATER ACOUSTIC POSITIONING SYSTEMS FOR MEC DETECTION AND REACQUISITION OPERATIONS

ESTCP Project MR-200734

JANUARY 2016

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14. ABSTRACT

The Nautical Ordnance Mapping And iDentification (NOMAD) is a long baseline acoustic positioning system that integrates high-accuracy time synchronization and wireless radio-modem telecommunications between bottom stations and a cabled pinger attached to a vessel-mounted surface station. The demonstration was performed August 2014 at Pat Mayse Lake, TX. Positioning accuracy in four separate pingerpole tests ranged from 30cm (mean) with standard deviation of 24cm to 65cm (mean) with a standard deviation 60cm, which include an estimated 15cm error due to the measured pingerpole tilt. Accuracies improved with experience, the better accuracies were achieved at the end of the field activities and are attributed to lessons learned from earlier deployments. Magnetometer data positioning proved more difficult. Average anomaly repeatability was 1.6m with a standard deviation of 0.9m. The ease of setup met its performance objectives; the whole system can be deployed and calibrated in 30 to 45 minutes, and retrieved in less than 10 minutes.

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EXECUTIVE SUMMARY

The Nautical Ordnance Mapping And iDentification (NOMAD) is a long baseline acoustic positioning system that integrates high-accuracy time synchronization and wireless radio-modem telecommunications between bottom stations and a cabled pinger attached to a vessel-mounted surface station. The pinger can be mounted on towed bodies, divers or ROVs. Demonstration of the NOMAD system occurred during August 2014 at Pat Mayse Lake, TX. The system's overall performance was assessed. Unforeseen hardware and software problems precluded additional tests to demonstrate anomaly reacquisition and ROV navigation. The positioning accuracy of the system in four separate pinger pole tests ranged from 30 cm with a standard deviation of 24 cm to 65 cm with a standard deviation of 60 cm. Those accuracy statements include an estimated 15 cm error attributed to the tilt of the pinger pole. Accuracies improved with experience, the better accuracies were achieved at the end of the field activities, and are attributed to lessons learned from earlier deployments. Magnetometer positioning proved more difficult. The reproducibility of twelve anomaly source locations from three independent surveys was 1.6 m with a standard deviation of 0.9 m. The cause of the degradation in accuracy from the pinger pole tests to the magnetometer tests is not confirmed, but is suspected to be attributed to a variable, 4.5 to 6 second latency in the NOMAD system. The ease of setup met its performance objectives; the whole system can be deployed and calibrated in 45 minutes or less, and retrieved in less than 10 minutes.

The demonstration showed hardware is working as expected but the software is not. The software does not automatically adjust position solutions for the depth measured at each bottom station or at pinger attached to the towed asset, which significantly affects the accuracy of the calculated position solutions. Depth sensor accuracy is affected by changes in its temperature, which requires cooling the sensor prior to initiating system calibration. The software is also prone to crashes. Additional software improvements are needed because a 4.5 to 6 second latency exists between the time of a ping event and that event being sent over the RS232 communication port.

The approximate retail cost of a NOMAD system, including four baseline stations, is $86K.

LIST OF ACRONYMS

CEHNC: US Army Corps of Engineers Engineering and Support Center, Huntsville
COE: Corps of Engineers
COTS: Commercial Off The Shelf
DGM: Digital Geophysical Mapping
DGPS: Differential Global Positioning System
EM: Electromagnetic
EMI: Electromagnetic Induction
ERDC: US Army Engineering Research and Development Center
FUDS: Formerly Used Defense Sites
GGA: Generalized Gradient Approximation
GPS: Global Positioning System
IMU: Inertial Measurement Unit
ISO: Industry Standard Object
MEC: Munitions and Explosives of Concern
NAD83: North American Datum 1983
NMEA: National Marine Electronic Association
NOMAD: Nautical Ordnance Mapping and iDentification
nT: Nanotesla
OPUS: Online Positioning User Service
RFR: Radio Frequency Radiation
RTK: Real Time Kinematic
TLT: Target Locating Transponder
USACE: US Army Corps of Engineers
UTM: Universal Transverse Mercator
UXO: Unexploded Ordnance
WGS84: World Geodetic System 1984

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1.0 INTRODUCTION

Munitions and Explosives of Concern (MEC) are known to exist in hundreds of lakes, ponds, rivers and coastal waters in and around the United States and its territories. Munitions response projects often focused on the MEC problem on land. However, regulatory interest has recently included the underwater MEC problem, and in particular, areas used by, or accessible to the public. Accurately positioning geophysical sensors in the underwater environment requires overcoming challenges such as boat motion, waves, currents and sound speed changes due to temperature, pressure and salinity. Layback positioning, or using the geometry of the towfish relative to the GPS receiver, often does not offer the accuracy needed for MEC investigations or requires a rigid towing system. Acoustic positioning systems are more accurate, but can be costly and require extensive calibration.

The **N**autical **O**rdnance **M**apping **A**nd I**d**entification (NOMAD) system is a long baseline (LBL) acoustic underwater positioning system that provides positioning and navigation tools for underwater ordnance detection and recovery operations. The system is designed to have positioning accuracies between 25 and 50 cm. The system hardware consists of any number of bottom stations (three were to be used in this demonstration), and a pinger unit that is mounted on towed or tethered platforms. The system will eventually support diver stations to be used by divers to navigate to and record information about underwater waypoints. This functionality is not available in the current configuration.

This final technical report details the demonstration work designed to assess the performance of the NOMAD system. NOMAD was built according to the "Design Plan for Underwater Acoustic Positioning Systems for MEC Detection and Reacquisition Operations, Phase 2", Project Number: MM-0734, dated April 2009. This plan was approved by the ESTCP in a memorandum from the ESTCP program office dated 1 February, 2010. NOMAD was built by Desert Star Systems, LLC.

1.1 BACKGROUND

The basic technologies for detecting underwater UXO are the same as those on land; however, the underwater environment poses a distinct challenge to positioning geophysical measurements, particularly when the need exists to compensate for current, wave action and wind when calculating accurate sensor positions. The use of LBL positioning systems offers the simplicity of position solutions that rely only on the speed of sound in water, thereby negating the need to compensate for all the variables that affect vessel-mounted systems. NOMAD is a LBL system that was designed to be rapidly deployable and capable of sub-meter positioning in support of MEC investigations.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this demonstration was to validate the NOMAD positioning system for underwater MEC detection operations. This demonstration consisted of using NOMAD system to position underwater geophysical mapping in a controlled, open-water environment. The design of this demonstration closely mimicked real-world scenarios in that:

1. Metal targets were dropped/emplaced into the water bottom,
2. NOMAD was deployed and integrated into a geophysical mapping survey of the area,
3. The system was recovered, the geophysical data processed and interpreted,

Using NOMAD to reacquire anomalies was originally part of the demonstration plan, but was not performed. Software limitations, software bugs and hardware breakdowns resulted in all available time and resources being required to accomplish the primary objective of assessing the system's overall performance.

1.3 REGULATORY DRIVERS

There are no promulgated regulatory drivers for this technology. Positioning and navigation accuracy are widely known in the munitions response industry to be among the primary drivers in operation efficiency and cost. Increasing anomaly location and reacquisition accuracies directly correlates to increased field operations efficiency and reduces project costs: anomaly investigation teams spend less time searching for anomalies and more time recovering anomalies.

The NOMAD system fills the technology gap for accurate underwater positioning and navigation solutions in a form factor that is easy to deploy, simple to calibrate and designed for underwater munitions operations.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The NOMAD system has three primary elements:

- An underwater acoustic positioning system. It is capable of precisely tracking a sensor towfish or providing navigation information for an autonomous underwater vehicle (AUV) during the mapping phase of a MEC project. During the target re-acquisition phase, the system has the capability to guide divers or a ROV back to mapped targets for identification.
- A GPS and acoustic based pinger-pole used to survey the location of the underwater positioning system following deployment. The pinger pole includes a differential GPS receiver and a GPS triggered pinger. By comparing momentary boat GPS positions and associated acoustic range measurements, the position of each baseline station is quickly and precisely fixed in real-world coordinates.
- Simple, task optimized software for the baseline surveys, mapping operations and target re-acquisition. By feeding precision sensor positions into the mapping software for the geophysical detection sensor or towfish, NOMAD provides a streamlined capability for geophysical surveying and target re-acquisition.

As described above, NOMAD is comprised of purpose-built acoustic positioning hardware, GPS timing hardware, radio link hardware, and specialized software to control the hardware and calculate positions. The following innovations have been integrated into NOMAD that forms the basis of this project:

- High accuracy timing synchronization: NOMAD achieves timing synchronization on the order of 100 micro seconds for all system components through GPS time signal and radio links at each bottom station. A surface buoy tethered to the bottom station uses GPS time signals to zero the bottom station clock every second, and uses an RF radio link to broadcast bottom station data to the control computer.

- Unlimited number of bottom stations: a key component to the implementability of LBL systems for munitions operations is to have a sufficiently large network of bottom stations so that large area coverage can be achieved. Currently the system software is limited to four bottom stations.

- Fixed mount for bottom stations' acoustic components: To minimize position error the bottom stations must be as stationary as possible and sufficiently proud of the sea floor to be effective. The tripod mounts are easily deployed from small vessels and designed to land up-right on the seafloor with the acoustic package situated 1m above the seafloor. The tripods hold the acoustic package in a fixed location eliminating error due to a moving acoustic package.

- Rapid baseline calibration of the bottom station network using a pinger-pole survey: To convert the local network of bottom station coordinates to real-world coordinates the geographic locations of each bottom station must be known. To achieve this, the

NOMAD system uses a pinger-pole survey to calculate bottom station coordinates. The pinger-pole survey consists of a vertical pole mounted to a surface vessel that has an acoustic target fixed at its bottom and a RTK DGPS mounted to its top. By navigating through the survey area with both the NOMAD acoustic system and GPS systems operating simultaneously, it is possible for the NOMAD software to rotate and translate the vessel path (as measured in the local bottom station coordinate system) to match the vessel path measured by the GPS system. This operation in turn provides the geographic coordinates of the bottom stations.

- Precise temperature compensation: Water temperature is one of the components to accurate speed of sound determinations. Each bottom station is equipped with a factory calibrated temperature sensor accurate to +/- 0.1° Celsius.

The primary components of NOMAD are illustrated in Figure 1 and described below:

- The tripod mounted underwater baseline stations **(A)** provide a precise position reference that remains stationary in the water column.
- Each baseline station is powered, precisely synchronized to GPS time and transmits ranging results via a radio modem mounted in an associated spar buoy **(B)** anchored above the baseline station.
- During the *baseline survey phase*, a pinger-pole **(C)** incorporating an acoustic pinger and a precision GPS receiver is used to calibrate the NOMAD baseline station array prior to mapping operations.
- Sensor towfish tracking during the *mapping phase* is facilitated by a small pinger **(D).**
- During the *target re-acquisition phase* divers navigate with the help of a tank mounted acoustic receiver **(E)** and a small navigation terminal **(F)**

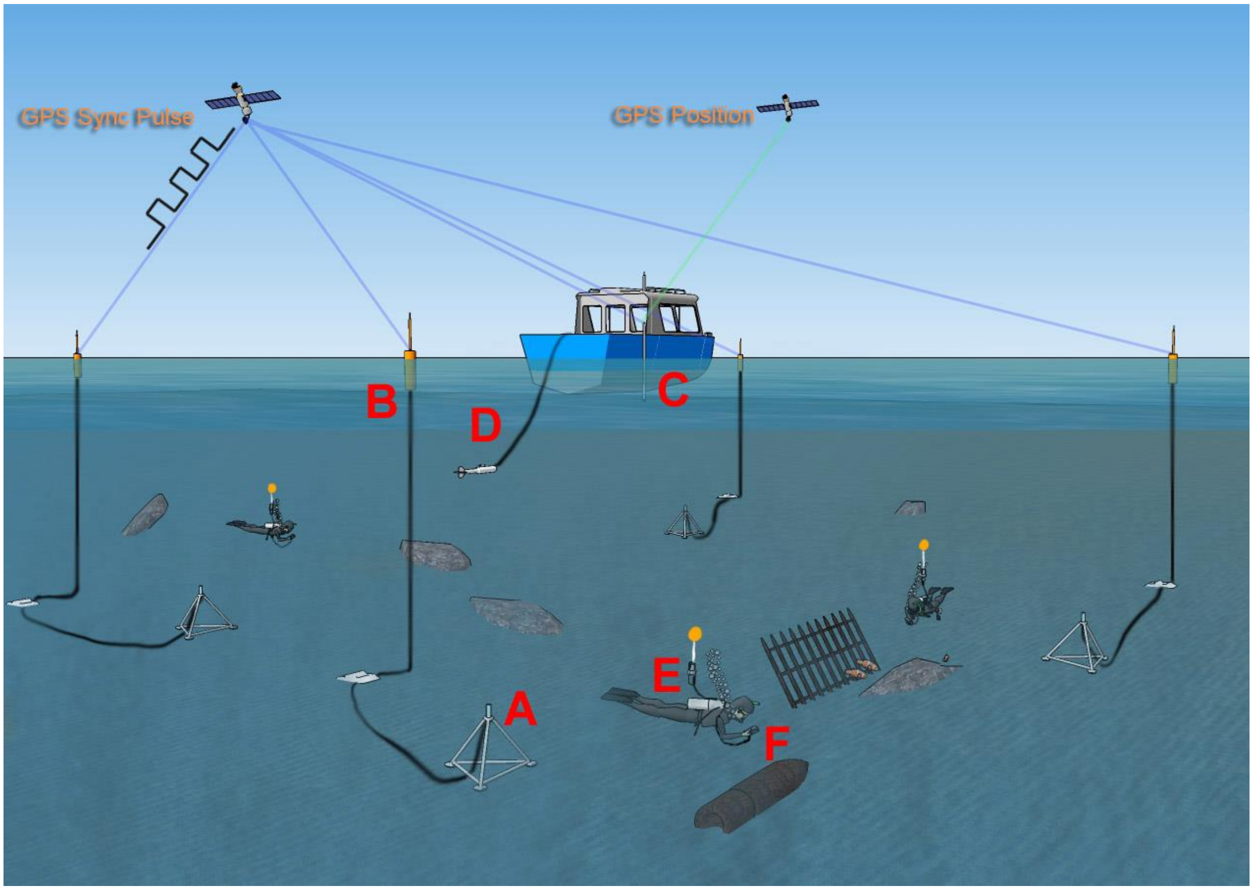


Figure 1: NOMAD schematic

2.2 TECHNOLOGY DEVELOPMENT

NOMAD is the culmination of integrating several existing LBL and GPS positioning technologies. These technologies are: commercial off the shelf long base line transponders, Aquamap Survey (a Desert Star product), PLATS (a Desert Star prototype LBL concept developed and tested for the Navy), GPS timing signals for system synchronization, and radio data links. Complete descriptions of AquaMap Survey and PLATS systems can be found in the Phase 1 demonstration plan (Flagg 2007). GPS timing signals and radio data links are common technologies used in many industries including geodetic surveying and geophysical surveying.

The need for a high accuracy underwater positioning system for munitions operations was recognized following a study of underwater positioning technologies conducted as part of the Army Environmental Quality Technology program in 2006 (USAESCH 2006). Following that study the Army Corps identified the AquaMap Survey system as a possible solution to underwater munitions response positioning and navigation needs. This system was identified through internet searches performed by USACE. USACE collaborated with Desert Star Systems, LLC to propose this ESTCP project, which was funded in Phase 1 to demonstrate AquaMap Survey along with a prototype, cabled, multi-reference long baseline system identified as PLATS. The results of the Phase 1 demonstration are presented in the Phase 1 In-Progress Review to the ESTCP program office in 2008 (Schwartz 2008) and additional details are

presented in the appendix to the Phase 2 Design Plan, which is included herein as Appendix A to this final plan.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY CONCEPT

The advantages of the NOMAD concept are that it is a rapidly deployed and rapidly calibrated LBL technology that can be used on any vessel of opportunity and seamlessly integrated into any system designed to accept National Marine Electronics Association Generalized Gradient Approximation (NMEA GGA) positioning strings. A significant advantage this system has over traditional transponder-based LBL systems is that NOMAD is a simple, pinger-based system. Accuracy is independent of tracked assed speed; it does not degrade as a function of tracked asset speed or range as do all transponder-based LBL systems. An advantage of this and all LBL systems is that most operations occur at approximately the same depth as the bottom stations, therefore minimizing performance degradation attributable to changes in the vertical sound speed profile within the water column.

Disadvantages of the NOMAD concept are that the range of coverage is limited by the number of baseline stations that are deployed, the position update rate is currently limited to 1Hz, and the position update rate must decrease with increased distance between bottom stations.

Other technologies that can be used for underwater munitions operations include COTS LBL systems and COTS ultra-short baseline (USBL) systems. COTS LBL technologies are limited by significant calibration processes and relatively low update rates, as well as degraded position accuracies associated with baseline stations that are suspended in the water column and subject to movement from current action. COTS USBL systems are limited by requiring highly sophisticated hardware, software and system calibration to compensate for vessel roll, pitch, yaw and heave. These systems are also limited by potential degradation if position accuracy associated with daily changes in the vertical sound speed profile through the water column.

3.0 PERFORMANCE OBJECTIVES

The performance objectives for this demonstration are listed in Table 1.

Table 1: Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Seed Item Location Accuracy	Average and standard deviation in the difference between seed item location and: a) interpreted anomaly location, and b) indicated location upon reacquisition	Detection list of seed items (detection locations compared to actual)	Δ Position offsets ≤ 0.65 m
		Reacquisition coordinates of seeded items (reacquired locations compared to actual)	Δ Position offsets ≤ 0.95 m
		Reported locations of Reacquired seed items (NOMAD reported compared to actual)	Δ Position offsets ≤ 0.35 m
		σ Position offsets ≤ 0.15 m	
Pinger pole Position Accuracy	Average and standard deviation in the difference between each NOMAD pinger pole position and the track of the RTK-DGPS positions of the pole	List of the shortest distance between each useable NOMAD pinger pole solution and the track of the pinger pole as recorded by the RTK-DPGS	Δ Position offsets ≤ 0.35 m σ Position offsets ≤ 0.15 m
NOMAD setup time	Time required to deploy and calibrate 4 NOMAD baseline stations	• Log of system deployment times accurate to 15 minutes	NOMAD setup time: < 45 minutes
Qualitative Performance Objectives			
Quality of dipole signatures	Cleanliness of dipole signatures	Pseudo color map of measured total field magnetometer data.	Dipole signatures exhibit regular, single-source characteristics.
Ease of use	Setup, deployment, operations and retrieval of the hardware, and merging the positioning data with the mag data	• Feedback from user(s) on usability of technology and time required	Feedback from field personnel indicates minor improvements, or no improvements are needed.

3.1 SEED ITEM LOCATION ACCURACY

The effectiveness of NOMAD to position geophysical data and then navigate a reacquisition effort to the interpreted anomaly locations was not assessed during the demonstration. Technical problems with the pole-mounted camera system precluded establishing accurate seed item locations, and the quality of the magnetometer data was not sufficient to accurately identify individual dipoles associated with individual seeds. Therefore seed item accuracy cannot be reported in the manner envisioned in the original survey design. However, three magnetometer surveys were performed over the target field and the difference in location of the analytic signal anomalies in each dataset were used to compare reproducibility of anomaly locations. Though not comprehensive, this method does provide a quantitative comparison of the geo-referenced locations of these anomalies, and does provide an indication of the reproducibility of NOMAD's positioning capabilities.

The metric for positional accuracies during data collection was for NOMAD interpreted anomaly positions to be offset less than or equal to 0.65 m. This metric was not met. The average difference between anomaly locations between the three datasets is 1.6m with a standard deviation of 0.9 m. Section 6.2 provides the details and basis for these calculations.

3.2 PINGER POLE POSITION ACCURACY

The purpose of this objective is to assess how well NOMAD calculates positions for each ping that is used for positioning solutions. The primary means of assessing positional accuracy was to compare NOMAD positions to RTK DGPS from four independent pinger pole surveys. This was achieved by navigating a checker-board pattern throughout the survey area at speeds of around 4 knots, correcting the pinger pole positions for tilt of the pole while the vessel was under way, then measuring the shortest distance between each NOMAD position and the track of the pole as recorded by the RTK-DGPS. This process is described in Section 5.5.1.

The metric for positional accuracies during data collection was for NOMAD positions to be within 0.65 m of the actual pole position, with standard deviations less than 15 cm. The first of these metrics was met but the second was not. The results of comparing the NOMAD and RTK-DGPS positions of the four surveys are tabulated below.

Table 2: Pinger pole Performance

Dataset	Mean Difference Between Positions	Standard Deviation Between Positions	Number Of Points In Comparisons
08182014_H	0.67 m	0.59 m	669
08182014_M	0.49 m	0.39 m	560
08182014_NO	0.49 m	0.53 m	323
08202014_J	0.30 m	0.24 m	595

3.3 NOMAD SETUP TIME

The setup time needed to deploy and calibrate NOMAD for munitions detection and reacquisition operations was a measure of the system's implementability. System deployment and calibration times were recorded for this metric. This metric focuses on NOMAD deployment and calibration, not on readying it or other geophysical systems or for surveys of reacquisition sorties. As such, start time was coincident with the launch of the first baseline station and the end time was after the completion pinger pole survey. The metric for this performance objective was for the NOMAD system setup time to be less than 45 minutes.

This objective was tested by timing how long it took to deploy each of the three working base stations from the boat and how long it took to perform a pinger pole survey with two north-south tracks and two east-west tracks (so that we had a tic-tac-toe pattern with four cross-over points). Each base station was first assembled on shore, then loaded on to the boat. It took approximately 5 minutes to deploy each base station once the boat arrived at the pre-determined base station location. It would take approximately 7 minutes to deploy a four station system, which is the normal configuration, and the value that will be used for this assessment. This deployment time included dropping the base station into the water, checking that it had landed on the lake bottom in the correct, upright position, and checking that the base station was receiving and transmitting data. It took on average 24 minutes to complete the baseline calibration survey, which is the process of establishing the local coordinates of the bottom station network, and that time would not increase for a four station system. The calibration time includes a lot of manual steps that were learned during the demonstration, and were found to be required to improve system accuracy (Section 5.4 identifies the steps in greater detail). Those manual steps could be automated to greatly reduce the calibration time—likely to five minutes or less. The pinger pole surveys took on average 4 minutes per line. Between 9 and 12 lines were collected for each, which is more than the four needed. For the purposes of assessing this metric the normal time spent would be about 16 minutes for four lines. The sum of all setup time activities is 47 minutes (7 min+24 min+16 min). This exceeds the objective by just two minutes, and as stated above, if the manual steps required to improve system accuracy are automated, the setup times will drop to well below the objective.

3.4 QUALITY OF DIPOLE SIGNATURES

A qualitative performance objective for NOMAD was to process the magnetometer data using the NOMAD positions and check the quality of the dipole signatures. The magnetometer data was to be assessed visually by looking for offset affects such as chevrons or irregular dipole signatures. The magnetometer data proved too difficult to use for its intended purpose because the quality of the dipole signatures was poor. This is believed to be due to two factors: 1) difficulties in merging the NOMAD and magnetometer data due to the variable lag in NOMAD position updates of between 4.5 and 6 seconds, and 2) varying sensor height above the lake bottom. The latter is likely to have occurred as a function of different survey speeds when going into or with the wind, as well as from difficulties in keeping the engines at similar low speeds from line to line. To check the latter, a qualitative assessment of north-going only, and south-going only survey lines from data files 08192014_C and 08202014_C were used to create

separate maps of the magnetometer data. The quality of the reproduced magnetic anomalies is improved suggesting sensor height is the primary reason for the poor quality of the dipole signatures. The data for file 08202014_C was collected in a Zamboni pattern; most of the western half of the lines were collected heading north, most of the eastern half heading south. The quality of the magnetic dipoles in this file are considered good.

3.5 EASE OF USE

Another qualitative objective that was assessed was the ease of use of the NOMAD system. Feedback from field personnel indicates that the hardware was simple, sturdy, easy to assemble and dissemble, and deployment was fast and easy. The software is easy to use. However it has bugs that cause the system to hang-up, plus the variable lag of between 4.5 to 6 seconds in fix position adds to the complexity in merging NOMAD data with geophysical data. Further, many of the manual steps required during in the calibration process could be automated. The areas the software can be improved are tabulated below:

Table 3: Suggested System Improvements

Issue or Problem	Description
Temperature compensation of the depth sensor.	The current system software does not use the bottom station temperature to calibrate the depth sensor, which requires pre-cooling the sensor before deployment.
Manual depth entries of the bottom stations during calibration	To improve system accuracy during the calibration process, the user must manually calculate averages of depth measurements from each bottom station and manually enter those in to the calibration routine
Manual calculation of the average location of bottom stations	To improve system accuracy during calibration process, the user must manually calculate average station coordinates during the calibration process
System hang-up	The software would periodically hang-up, which always required a software re-start (but never a computer reboot)
Manual input of rover pinger	The software does not automatically take the depth of the towfish pinger, which greatly complicates maintaining an accurate depth for the towfish during surveys.

4.0 SITE DESCRIPTION

4.1 SITE SELECTION

The demonstration was conducted at Pat Mayse Lake, Lamar County, TX. Pat Mayse Lake is located 12 miles north of Paris, TX and 123 miles northeast of Dallas. Pat Mayse Lake is part of the Former Camp Maxey Formerly Used Defense Site (FUDS) (Figure 2). The lake was selected because previous underwater surveys (Dawson-Zapata, 2012) had shown that the eastern part of the lake had areas of relatively flat bathymetry and free of obstructions. Additionally, the lake is managed by the Corps of Engineers, and the survey team was able to use the local office for logistical support.

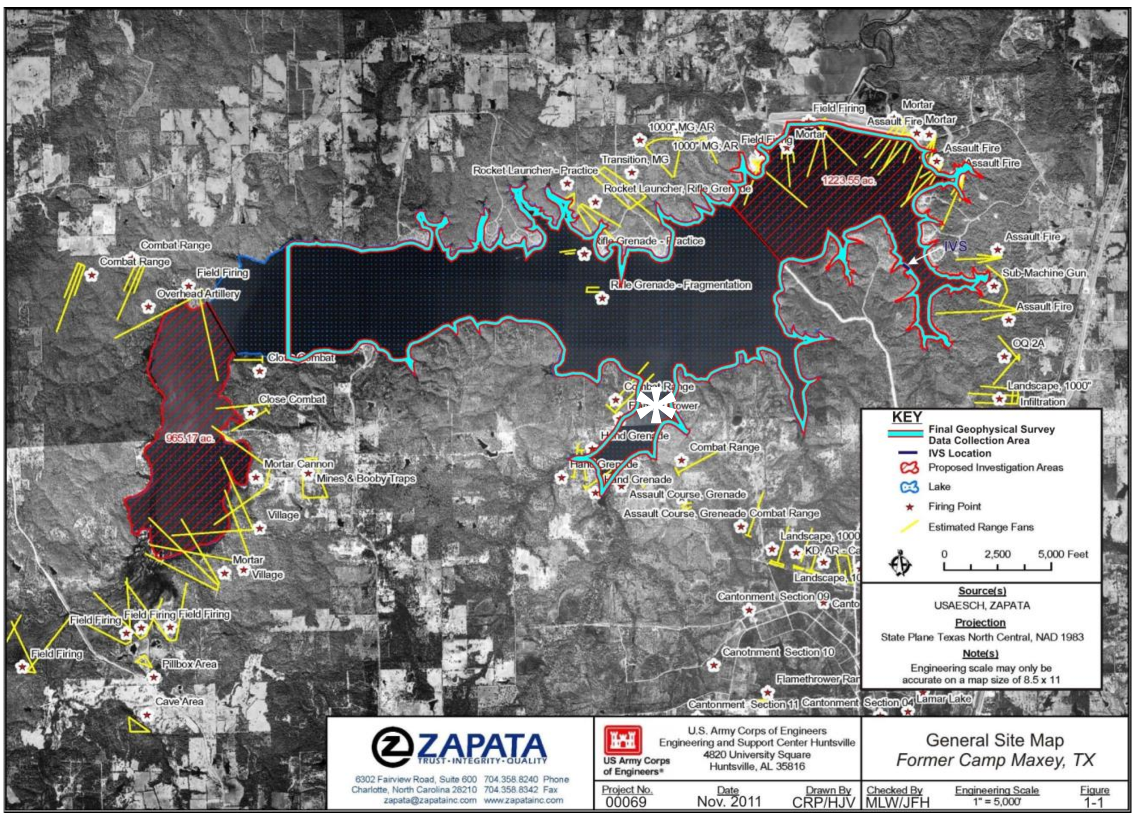


Figure 2: Site Map. The white asterisk indicates the location of the demonstration

4.2 SITE HISTORY

The 41,128 acre former Camp Maxey was activated as an infantry training camp in 1942 and was used for training through until May, 1947 (USACE, 2000).

The lake is an artificial reservoir constructed by the Army Corps of Engineer in 1967. The area of the demonstration is near, but not on, a historical range fan.

4.3 SITE GEOLOGY

The lake geology consists of a thin layer of sediments overlaying bedrock. The geological conditions did not adversely affect the magnetometer or acoustic positioning system.

4.4 MUNITIONS CONTAMINATION

No known munitions contamination exists in the area of the demonstration.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The NOMAD testing and evaluation had two components: 1) test the accuracy of the system using the pinger pole and 2) test the accuracy of the system when used to position magnetometer data. The pinger pole test places the NOMAD pinger directly under the GPS antenna, or if the pole is not vertical, provides a simple means of calculating pinger to GPS antenna offset using measured tilt data. The pinger pole test provides a simple method of comparing the accuracy of NOMAD position solutions by direct comparison to RTK-DGPS position solutions.

The second test was to position magnetometer data using NOMAD position solutions when the NOMAD pinger is mounted on the front of the magnetometer. This test requires the magnetometer be flown at constant depth and far from the tow vessel, which was achieved by suspending the magnetometer from a floatation device, which was towed approximately 15 meters behind the tow vessel. This configuration precluded magnetic interference from the survey vessel's engines and generator. The magnetometer was suspended below the flotation device so that it would be approximately 1.5m above the lake bottom in the target field. To show reproducibility in this test, two different bottom station deployments were required, which demonstrates NOMAD's capability to reproduce accurate, real-world coordinates after the bottom stations have been moved (or redeployed at some later date).

The general process for NOMAD positioning in geophysical operations is as follows: 1) deploy the bottom stations, 2) establish the local network geometry of the bottom stations on the lake bottom (referred to as baseline calibration), 3) perform a simple pinger pole survey to collect information needed to rotate and translate the local network to real-world coordinates (in our case, UTM Zone 15N, WGS-84 datum), 4) transfer the pinger from the pinger pole to the geophysical asset (e.g. magnetometer, ROV, diver), then 5) perform geophysical operations. Any time one or more of the bottom stations is moved, step 2 must be performed before geophysical operations resume, and step 3 must be performed either before (preferred) or after geophysical operations if the data is to be rotated and translated to real-world coordinates.

Since pinger pole surveys were used to quantify NOMAD accuracies in (1) above, the pinger pole surveys for this demonstration were more comprehensive than needed for a normal calibration in order to provide a greater number of data points for the comparison analysis. Normal calibration only requires four survey lines, two each in one direction and two each normal to the first pair, forming a tic-tac-toe pattern. Each location where the lines cross provides a unique, co-located coordinate in each system, which is the information needed to rotate and translate the local system to the world system. The pinger pole surveys for this demonstration had between 12 and 16 lines. The Gantt chart below provides the sequence of testing events.

Table 4: Gantt Chart Of Field Activities

Activity	8/18/2014		8/19/2014		8/20/2014	
	Morning	Afternoon	Morning	Afternoon	Morning	Afternoon
Deploy Reference Stations #1						
Pinger Pole Survey 08182014_H						
Pinger Pole Survey 08182014_M						
Pinger Pole Survey 08182014_N&O						
Reconfigure vessel for magnetometer surveys						
Magnetometer Survey 08192014_C						
Magnetometer Survey 08192014_E						
Deploy Reference Stations #2						
Magnetometer Survey 08202014_C						
Reconfigure vessel for pinger pole surveys						
Pinger Pole Survey 08202014_J						

5.2 SITE PREPARATION

Site preparation consisted of a multi-beam environmental survey of the demonstration area, placing a string of medium Industry Standard Object (ISO) pipe sections along a single line in 3.5 to 4.5 meters of water, and establishing a temporary base station for the RTK DGPS.

5.2.1 ENVIRONMENTAL SURVEY

The environmental survey consisted of a RESON multibeam survey. The RESON system was integrated on to the survey vessel provided by ERDC. Figure 3 shows the bathymetric map produced of the demonstration site. The waypoints in Figure 3 labeled 4000, 4000a, 4001, 4001a, 4002 and 4002a are the approximate locations, at the water surface, where bottom stations were dropped. The other waypoints shown on the map were used by the boat pilot in planning track lines for the various surveys. None of the waypoints were used in the data analysis or interpretations for this report.

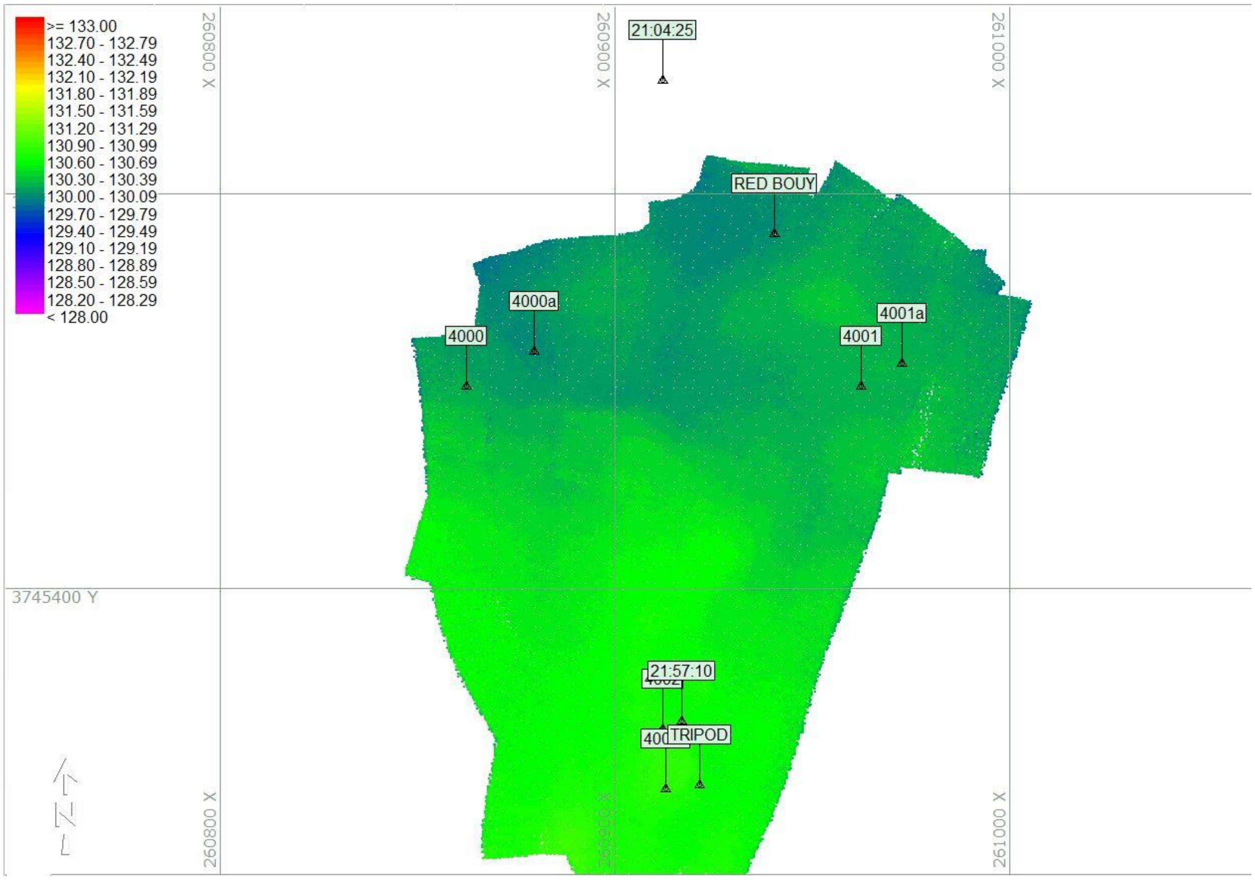


Figure 3: Bathymetric map of the demonstration area. Elevations are Geoid heights, in meters.

The RESON system can also produce backscatter images, similar to side scan sonar images that can be used to assess bottom conditions and identify potential obstructions. Figure 4 shows one of the images produced during this survey. No significant bottom obstructions were observed in the area of the demonstration.

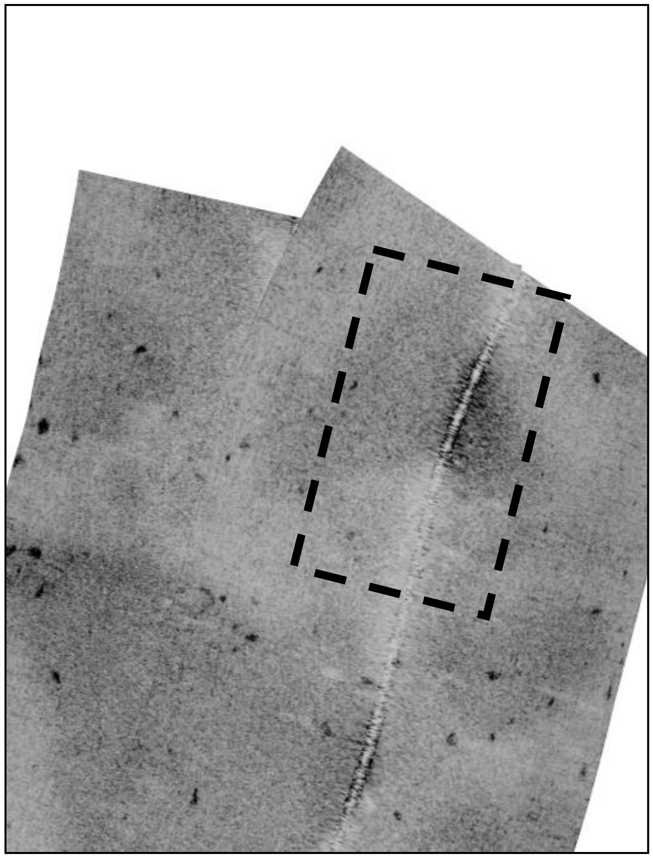


Figure 4: Backscatter image of the lake bottom and approximate location of the demonstration area (in the dashed rectangle). No significant obstructions are visible in the demonstration area.

5.2.2 SEED ITEM PLACEMENT

Medium ISO pipe sections were used for the 15 seeds. These are standard Schedule 40 steel pipe section eight inches long. They were tied onto a length of rope either 3 or 5 meters apart. The size of the seed(s) is listed in Table 5 and the seed placement design is shown in Figure 5.

Table 5: Seed item size

Length	Outside Diameter (in)	Wall Thickness (in)
8"	2.375	0.154

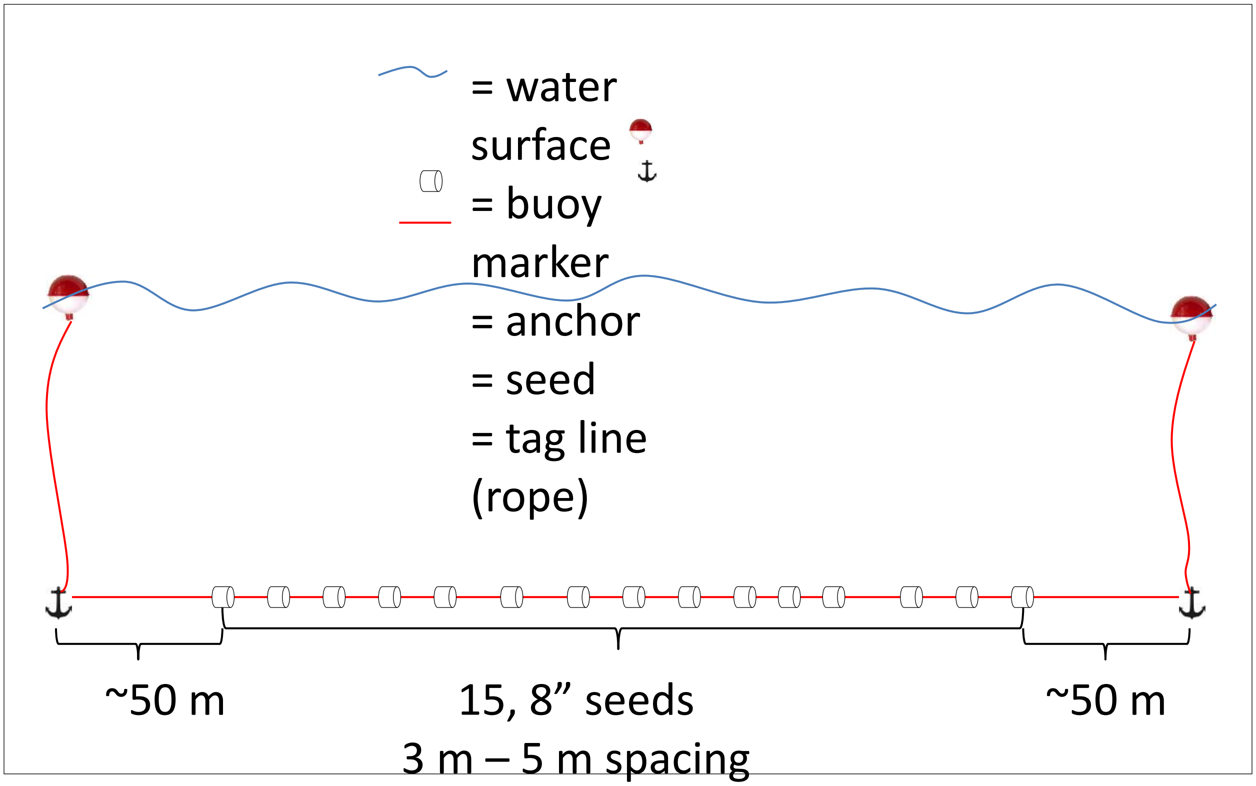


Figure 5: Seed layout

The seeds were placed by deploying the first anchor over the bow of the boat. The boat then slowly backed up and the seeds were lowered into the water. When the last seed was deployed, the tag line was pulled taunt and the final anchor was deployed.

5.2.3 TEMPORARY CONTROL POINT

A temporary control point was established near the demonstration area. Its coordinates were established by uploading several hours of static position data to OPUS (Online Positioning User Service) to obtain centimeter level accuracy for the base station's latitude, longitude and height above ellipsoid. A survey pin and witness marker were used to reacquire the location from day to day. Figure 6 shows the base station. For reference, the demonstration area is approximately midway to the far shore in the background.

Figure 6: Base station location

5.3 SITE SPECIFICATION

The system specifications are described in Section 2 of this report.

5.4 CALIBRATION ACTIVITIES

NOMAD calibration would normally have two steps: 1) monitor ambient acoustic noise and set ping detection thresholds using the simple NOMAD interface to do so, and 2) have the NOMAD software automatically perform the baseline calibration. Because the software does not yet use either the temperature or depth sensor data transmitted by the bottom stations, this last step was performed manually as follows:

1- Acclimate bottom station to ambient bottom temperatures (~5 minutes at depth, followed by raising to surface and turning the unit off then on and re-dropping it to the lake floor).
2- Collect 5 to 7 depth measurements, and average them.
3- Enter depth value in to NOMAD software
4- Collect 5 to 7 local network calibration measurements (the software automatically calculates local bottom station network coordinates, but there are small differences of one to five centimeters in station coordinate between runs of the calibration routine. We found taking the average of 5 to 7 measurements improved overall system accuracy.)

5- Manually enter the local coordinates for each bottom station in to the software
6- Manually enter the depth of the pinger (which is attached to the geophysical asset) in to the software
7- NOMAD system now ready for geophysical operations

A visual track of the NOMAD position solution is plotted on the graphical user interface. Visual monitoring of the track-plot was used to verify the system was operating. The GUI also provides an error estimate, which is calculated as the residual distance between the calculated pinger position to the center of the 3-D polygon formed by the intersection of the spheres formed around each bottom station, having radii equal to the measured distance from the pinger to the station. When errors on the order of 5 to 10 cm were achieved after calibration, the system was deemed to be operational.

5.5 DATA COLLECTION

5.5.1 PINGER POLE SURVEYS

Two triangular deployment patterns were set up to test the system's reproducibility performance. The first deployment placed the bottom stations at an average distance of 90 meters and a depth of 3 to 4 meters (Figure 7). The second deployment placed the bottom stations at an average distance of 100 meters and a depth of 3 to 4 meters (Figure 8:). Figure 9 shows the three buoys with the Radio Frequency Radiation (RFR) radio modems and GPS clocks that are tethered to the bottom stations.

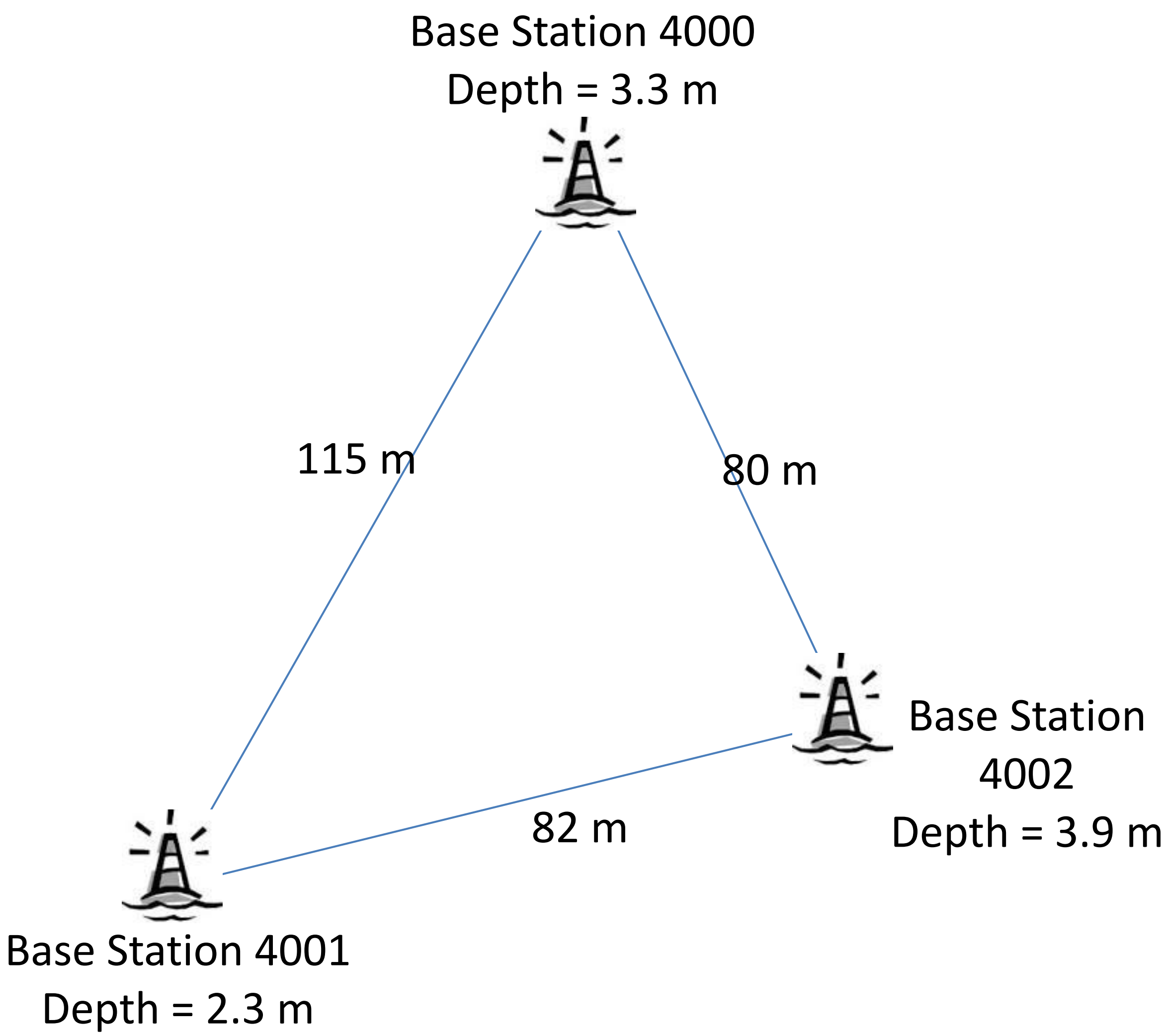


Figure 7: Deployment #1 layout

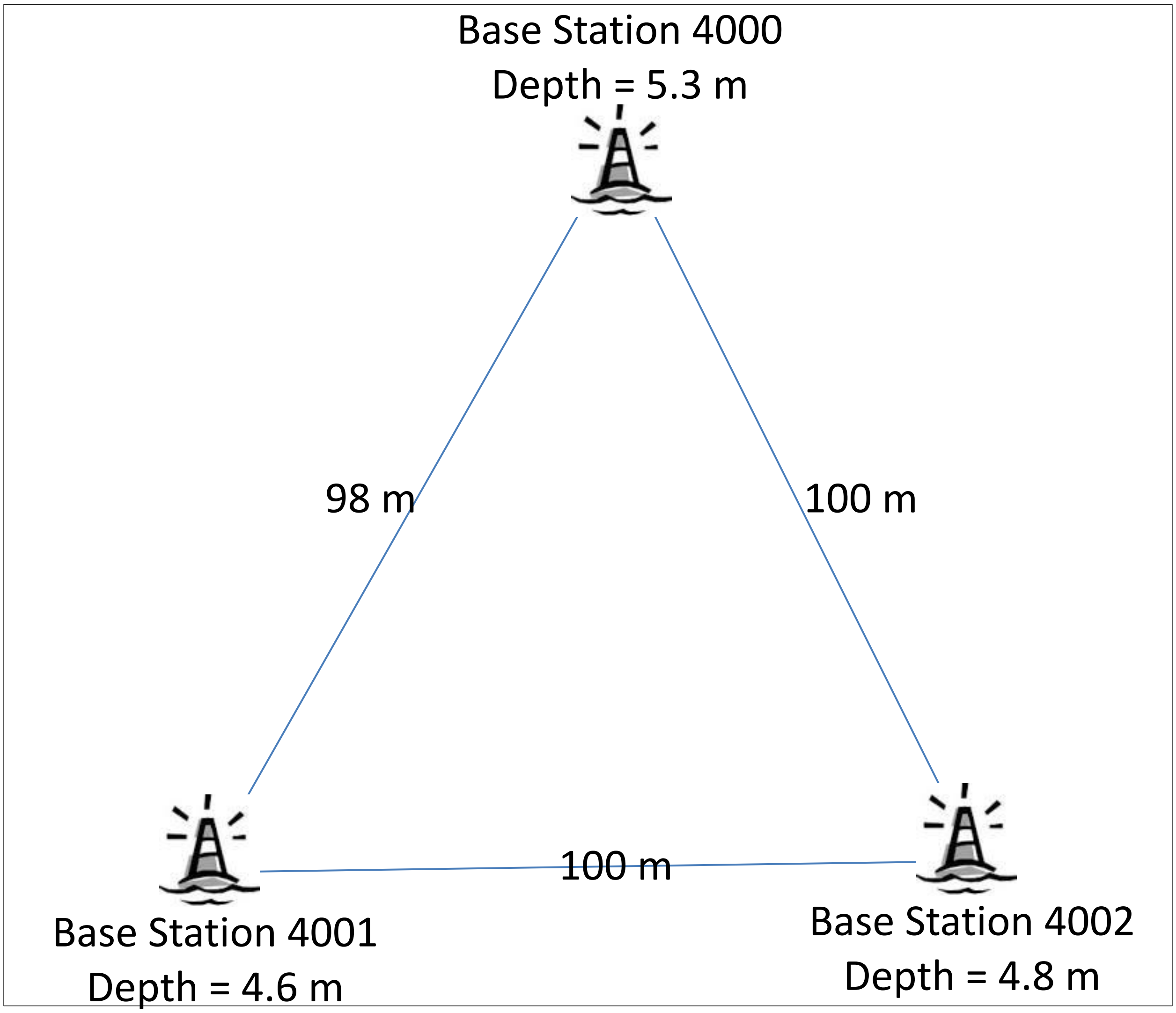


Figure 8: Deployment #2 layout

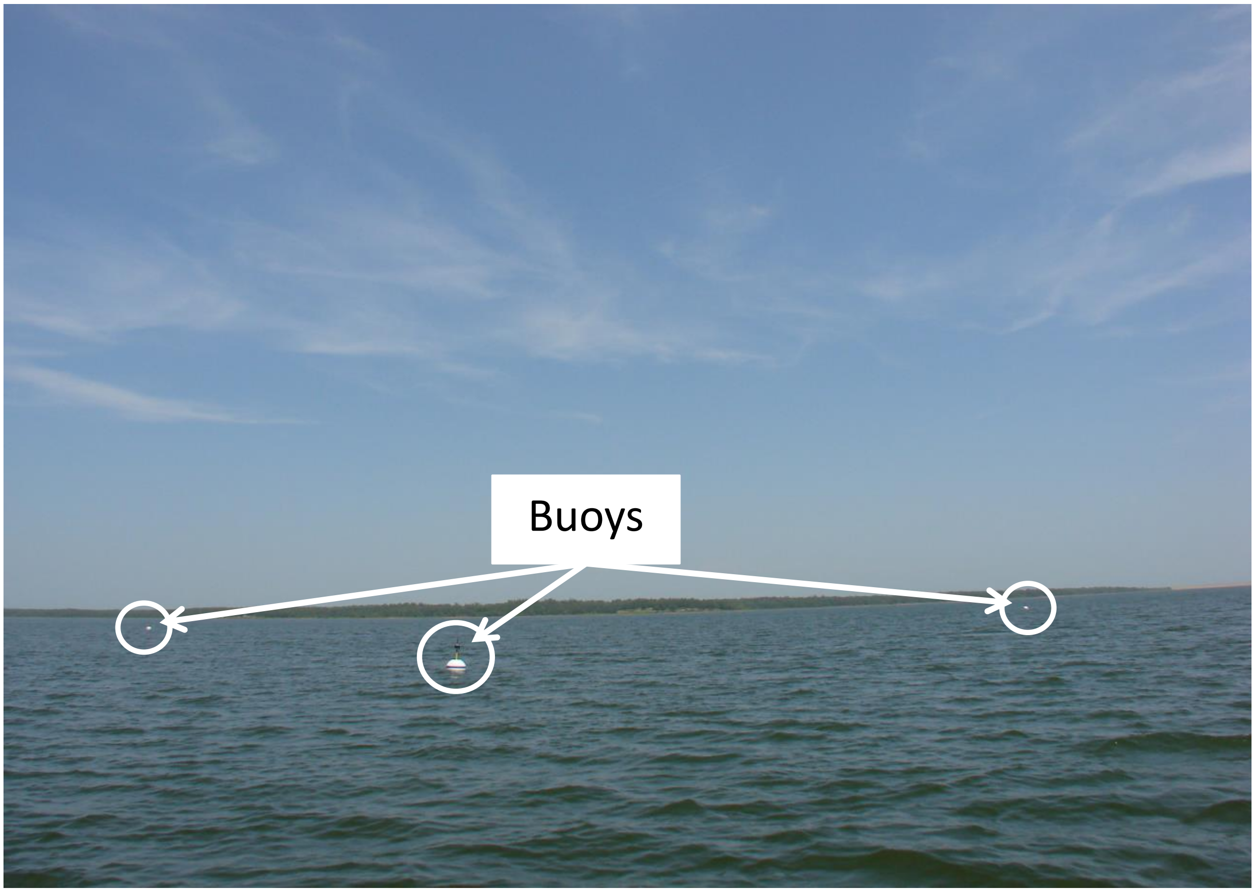


Figure 9: NOMAD system deployed for survey

5.5.1.1 NOMAD BOTTOM STATION DEPLOYMENT

Once drop locations are established (Figure 7 and Figure 8), the tripods are set up and connected to the buoys as seen in Figure 10. The RFR units, which sit on short poles extending above the buoys and house the RF communications and GPS clocks, were not connected to the top of the buoy until actual deployment. This prevents damage that may occur during transportation to and from the site.

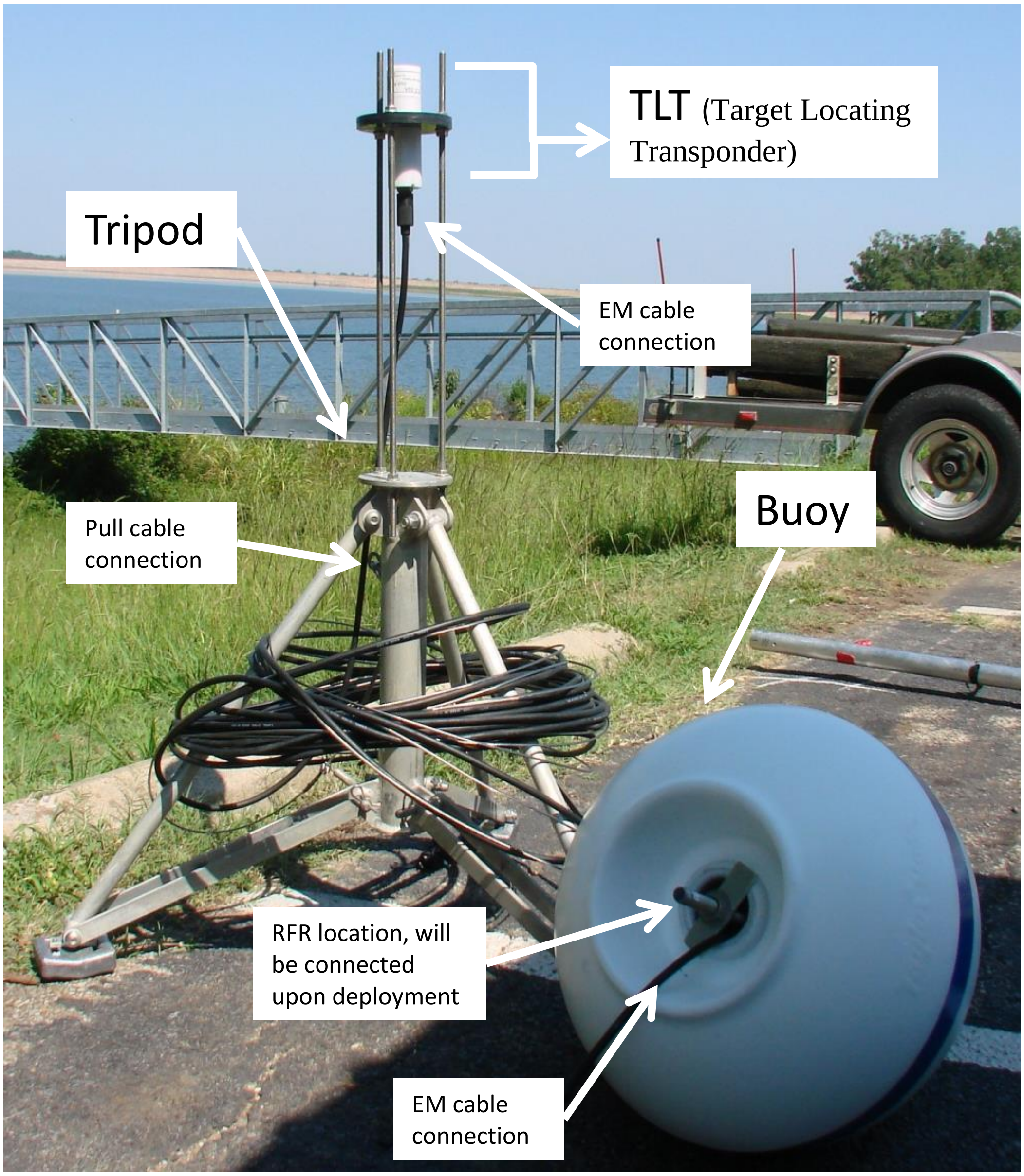


Figure 10: Tripod and buoy assembly

The assembled tripods are then transported to the pre-designated locations (refer to Figures 7 and 8). The RFR units are connected to the top of the buoy (Figure 11) and then the tripod is dropped over-board, making sure that it falls straight down (Figure 12). The last step is to attach the RFR whip antenna (Figure 13) before releasing the buoy from the side of the vessel (Figure 14). This is done to minimize the likelihood of breaking the antenna during buoy deployment.

Figure 11: Tripod and buoys ready for deployment Note RFR attached to the far buoy.

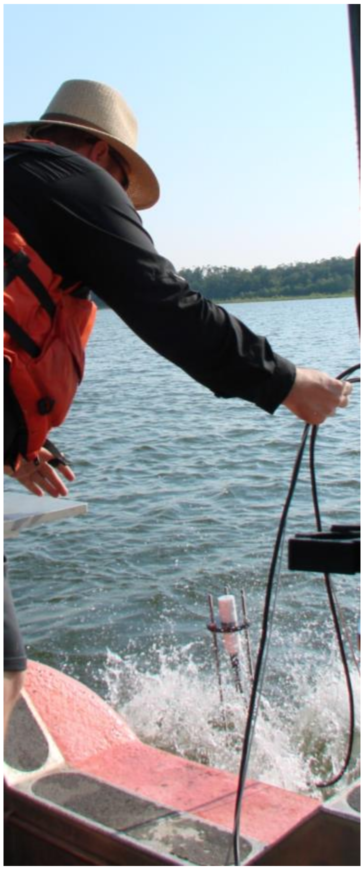


Figure 12: Tripod deployment

Figure 13: Attaching RFR antenna

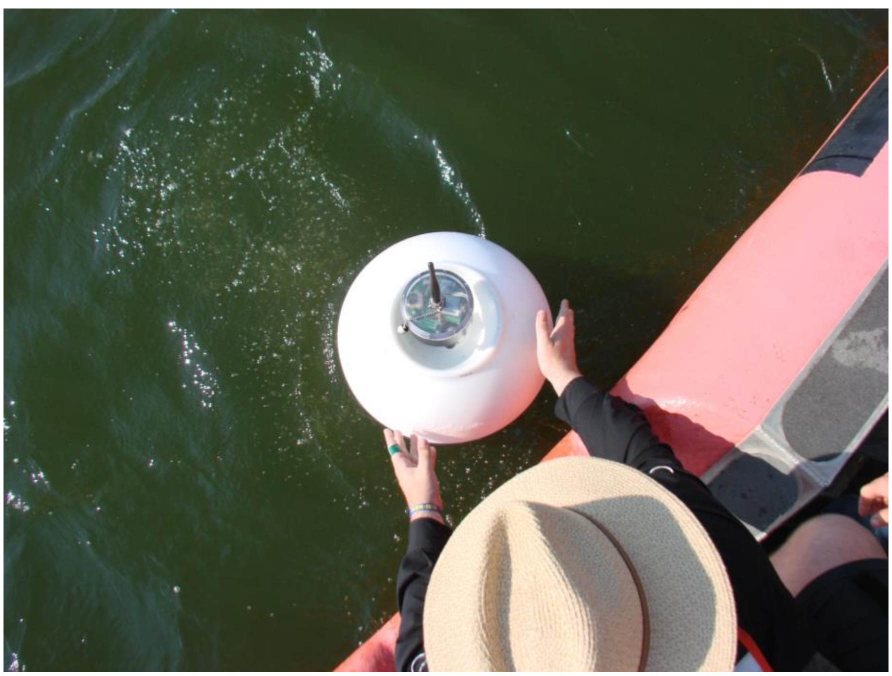


Figure 14: Releasing the buoy

5.5.1.2 PREPARE PINGER POLE FOR SURVEY

The ERDC boat had a pinger pole brace mounted on the starboard side so that the pole could be rotated on to the vessel for transport (Figure 15) or in to the water for surveys. The mount is designed such that, when the boat is traveling at survey speeds of ~4 to 5 knots, the pinger pole will be near perpendicular to the water surface. For this test a 5-meter pinger pole was manufactured. The pinger pole was deployed by rotating the arm of the pole in to the water (Figure 16) while the boat is at idle, and tightening down the braces to lock the pole in place. (Figure 17). A guy-wire (1/4” rope) tied near the middle of the pole is then run forward and attached to the davit shown in Figure 15. This helps keep the pole from bending while at survey speed. The last step is attaching the RTK-DGPS antenna to the top of the pole (Figure 18). Figures 17 and 18 also show the location of the tilt meter, wrapped in red next to the GPS antenna mount.

Figure 15: Pinger pole location during transport.

Figure 16: Pinger pole deployment

Figure 17: Pinger pole deployed.


Figure 18: RTK DGPS mounted on top of pinger pole

5.5.2 MAGNETOMETER SURVEYS

Three magnetometer surveys were performed. Two were performed using the bottom station network for deployment #1 of the pinger pole surveys, and one for deployment #2 (see Table 6 in the next section for a list of dataset files associated with each bottom station deployment). All data was collected in a general north-south direction to align with the seed tag-line. The first two datasets were collected with sequential lines from west to east (e.g. north on line 1, south on line 2, etc.). The last dataset was collected in a Zamboni pattern, with the west half of the data collected in one direction and the east half in the opposite direction (e.g. north on line 1, south on line 10, north on line 2, south on line 11, etc.).

As explained in Section 5.1, the magnetometer needed to be flown at constant depth and far from the tow vessel. This was achieved by suspending the magnetometer from a floatation device that was towed approximately 15 meters behind the tow vessel. The magnetometer was suspended below the flotation device so that it would be approximately 1.5 m above the lake bottom in the target field. Figure 19 shows the NOMAD pinger attached to the magnetometer. The pinger was attached below the towfish because the towfish was flying above the bottom stations in the water column. This configuration minimized shadowing the pinger signal through the towfish itself. Figure 20 shows the flotation device under tow during a survey.

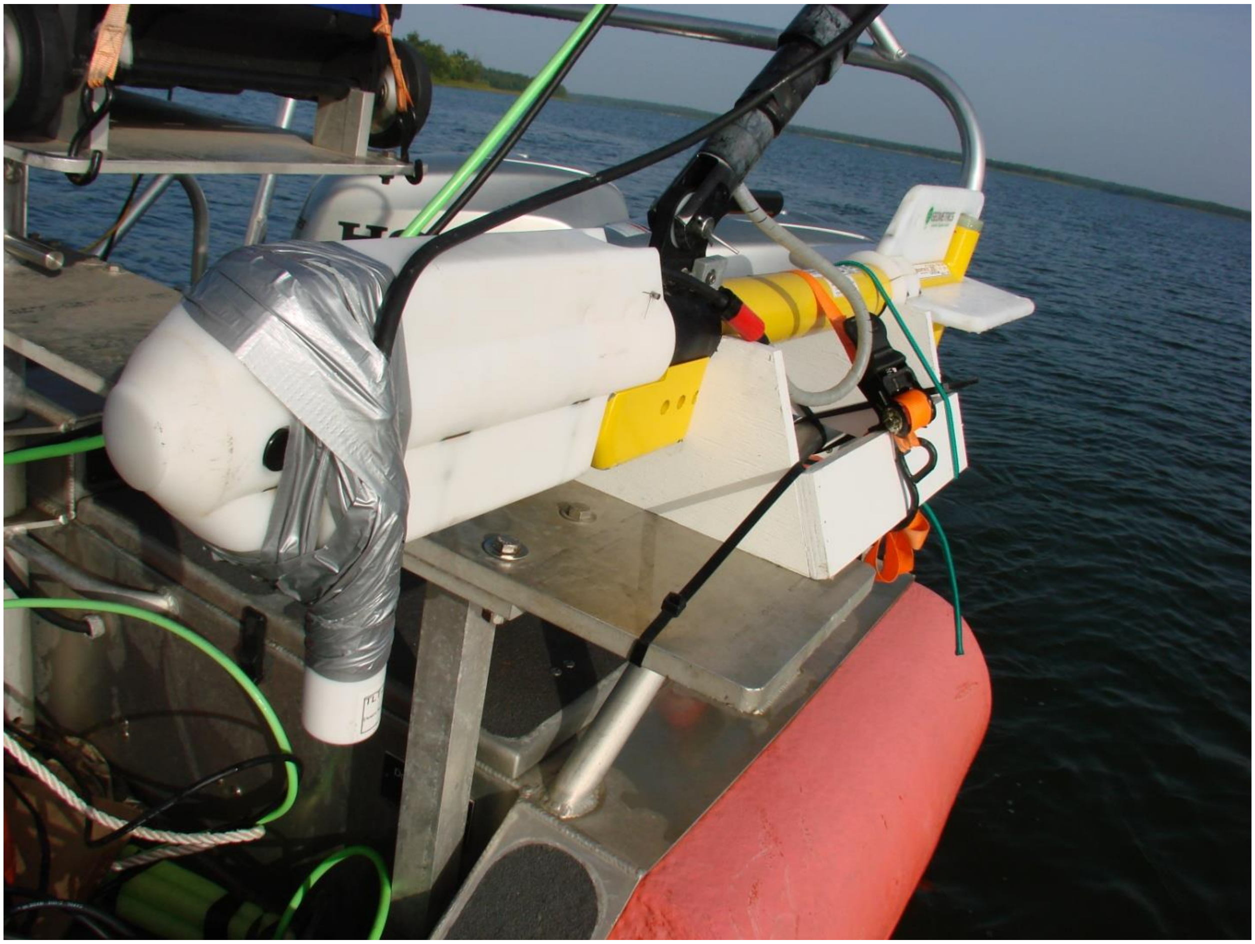


Figure 19: NOMAD pinger attached to the magnetometer towfish.

Figure 20: Magnetometer survey under-way

5.6 DATA SUMMARY

Four pinger pole and three magnetometer datasets were collected. Each is described in Table 6

Table 6: Demonstration Data Files

Dataset	Data Files	Survey Activity	Bottom station Deployment
08182014_H	Nomad_08182014-h.survey, Nomad_08182014-h.survey.GPS.gps, Nomad_08182014-h.survey.LineNumber, Nomad_08182014-h.survey.SerialDevice.imu, Nomad_08182014-h.survey.SerialDevice.nomad	Pinger pole Survey	#1
08182014_M	Nomad_08182014-m.survey, Nomad_08182014-m.survey.GPS.gps, Nomad_08182014-m.survey.LineNumber, Nomad_08182014-m.survey.SerialDevice.imu, Nomad_08182014-	Pinger pole Survey	#1

	m.survey.SerialDevice.nomad		
08182014_N&O	Nomad_08182014-n.survey, Nomad_08182014-n.survey.GPS.gps, Nomad_08182014-n.survey.LineNumber, Nomad_08182014-n.survey.SerialDevice.imu, Nomad_08182014-n.survey.SerialDevice.nomad Nomad_08182014-o.survey, Nomad_08182014-o.survey.GPS.gps, Nomad_08182014-o.survey.LineNumber, Nomad_08182014-o.survey.SerialDevice.imu, Nomad_08182014-o.survey.SerialDevice.nomad	Pinger pole Survey	#1
08202014_J	Nomad_08202014_j.survey, Nomad_08202014_j.survey.GPS.gps, Nomad_08202014_j.survey.LineNumber, Nomad_08202014_j.survey.SerialDevice.imu, Nomad_08202014_j.survey.SerialDevice.nomad	Pinger pole Survey	#2
08192014_C	Nomad_08192014-c.survey, Nomad_08192014-c.survey.GPS.gps, Nomad_08192014-c.survey.LineNumber, Nomad_08192014-c.survey.SerialDevice.nomad Nomad_08192014-c.Survey.882.GEOMAG	Mag Survey	#1
08202014_C	Nomad_08202014_c.survey, Nomad_08202014_c.survey.GPS.gps, Nomad_08202014_c.survey.LineNumber, Nomad_08202014_c.survey.SerialDevice.nomad Nomad_08202014_c.Survey.882.GEOMAG	Mag Survey	#1
08202014_E	Nomad_08202014_e.survey, Nomad_08202014_e.survey.GPS.gps, Nomad_08202014_e.survey.LineNumber, Nomad_08202014_e.survey.SerialDevice.nomad Nomad_08202014_e.Survey.882.GEOMAG	Mag Survey	#2

6.0 DATA ANALYSIS AND PRODUCTS

Pinger pole data analysis was performed in the steps outlined below. More detail on this processing is provided in Section 6.1.

1- Qualitative review of GPS track-plots
2- Delete spikes in the NOMAD track-plot
3- Correct the NOMAD track-plot for minor tilt in the pinger pole using the tilt meter data
4- Identify common points in the NOMAD and GPS track-plots; locations where east-west lines intersect north-south lines, and rotate and translate the NOMAD coordinates to real-world coordinates using Geosoft's Warp Dataset routine
5- Calculate the shortest distance from each NOMAD position to the GPS track-plot
6- Calculate the mean and standard deviation of the distances calculated in step 5

Magnetometer data analysis was performed in the general steps outlined below. More detail on this processing and the extra steps required are provided in Section 6.2.

1- Filter the magnetometer data to remove diurnal effects and heading errors
2- Remove data spikes and 50 cm shifts in the NOMAD data
3- Interpolate positions for all magnetometer measurements based on nearest NOMAD points
4- Apply time lag correction to all position data
5- Identify anomalies common to the three magnetometer data sets and calculate distances between each
6- Calculate average and standard deviation of the distances calculated in step 5.

6.1 PINGER POLE DATA ANALYSIS

Pinger pole data processing was performed in the simple, linear fashion described in Section 6.0 above. Early during the pinger pole analysis a large, inconsistent latency of between 4.5 and 6 seconds was discovered in the NOMAD data. This issue was not observed during the field work because the RTK-DGPS and NOMAD track-plots observed in real-time looked virtually identical. The latency was found to vary over the course of the 08202014_J data file. Similar latencies were observed in all other datafiles. Latency values were determined by comparing time stamps in the NOMAD and GPS data streams at known locations in the track-plots where east-west lines cross north-south lines. The latency was later confirmed during the magnetometer data analysis where an approximate 5.2 second latency was used in the final step of data preparation to produce magnetometer data maps with the least amount of zig-zag patterns in anomalies and background structure. Table 7 summarizes the latency analysis performed on the 08202014_J data file.

Table 7: Latency Analysis on Data File 08202014_J

Common Point #	NOMAD Timestamp	RTK-DGPS Timestamp	Difference (seconds)
1	17:40:16.37	17:40:10.68	5.69
2	17:36:09.62	17:36:03.50	6.1
3	17:31:20.59	17:31:13.80	6.8
4	17:43:54.55	17:43:48.07	6.48
5	17:49:24.45	17:49:19.39	5.05
6	17:27:41.81	17:27:36.65	5.15

The track-plots of the GPS and NOMAD pinger pole surveys are very similar. There are simply large time differences between when the two data streams were received at the MaglogNT computer. This suggests the latency issue is due solely to the NOMAD software. The large and variable latency necessitated a somewhat complicated method to assess the reported pinger pole position accuracies. The steps below were used to assess NOMAD pinger accuracies. Each step is described in further detail in subsequent sections.

1- Qualitative review of the RTK-DGPS data stream
2- Remove spikes from the NOMAD data
3- Account for offset between NOMAD pinger and GPS antenna
4- Rotate and translate the NOMAD data into the UTM Zone 15N coordinate system
5- Calculate the shortest distance from each NOMAD point to the line created by the two nearest GPS locations
6- Calculate statistics on the distances measured in step 5.

Each of these steps is described further below.

6.1.1 QUALITATIVE REVIEW OF RTK-DGPS DATA STREAM

The individual track-plots for each GPS file were reviewed for indications of bad data points. Only RTK-FIX (quality indicator 4) positions were retained. Track-plots were viewed at small scales to identify any spikes or features in the course over ground that were not consistent with the normal progress of the vessel through the water. None were noted and the entire dataset was used as recorded.

6.1.2 REMOVE NOMAD DATA SPIKES

Two types of position errors occurred during the surveys: gross errors (spikes), and a ~50 cm shift left or right error that would last for several seconds. The former were easily identified and deleted as illustrated in Figure 21, panels A and B. The cause of these spikes is unknown. The gross errors (spikes) are likely attributed to reverberation and multi-path associated with working in shallow water depths of 4 to 5 m with a hard, clay bottom. There are two possible causes of the ~50 cm shift errors: 1) the direct signal path may have temporarily been obstructed to one of the base stations, and the station instead triggered on a slightly refracted multi-path signal, or 2) changing signal propagation conditions, such as very early multipath causing destructive interference with the direct signal, which may have weakened the direct signal and caused a

detection delay. Additional tests would be required to confirm these potential sources, and would require firmware modifications to measure the full scale amplitude of the signal about 0.75 to 1 ms after initial detection.

Correcting the ~50 cm shift errors was done manually and required careful review of the track-plots at small scales. All observed instances were deleted as illustrated in Figure 21 panels C and D. Since the pinger pole data was used to assess NOMAD accuracies, all spike and ~50 cm shift errors were deleted from the datasets and not included in the statistics in step 6.

6.1.3 ACCOUNT FOR OFFSET BETWEEN NOMAD PINGER AND GPS ANTENNA

The accuracy of the pinger pole survey is dependent on keeping track of where the pinger is located with respect to the GPS antenna. This was accomplished using an Applied Geomechanics tilt meter. The specific sensor used was prone to interference from vibrations due to boat and generator motors, and therefore instantaneous measurements were not used. The mean roll and pitch of the vessel during the survey was used to estimate the pinger location with respect to the GPS antenna in terms of offset along-track and offset across-track of the boat's progress through the water. An additional offset was required to account for a 10 cm across-track bend in the aluminum pinger pole that was discovered and measured during demobilization. Errors due to roll and pitch were minimized during the surveys by instructing the crew to remain stationary during pinger pole survey operations.

The maximum error in the corrected pinger position with respect to the GPS antenna due to roll and pitch is estimated to be 15 cm. This is based on a qualitative assessment in the accuracy of the measured tilt being within 1.5 degrees of the actual tilt. The total distance between the pinger and GPS antenna was 5.1 m.

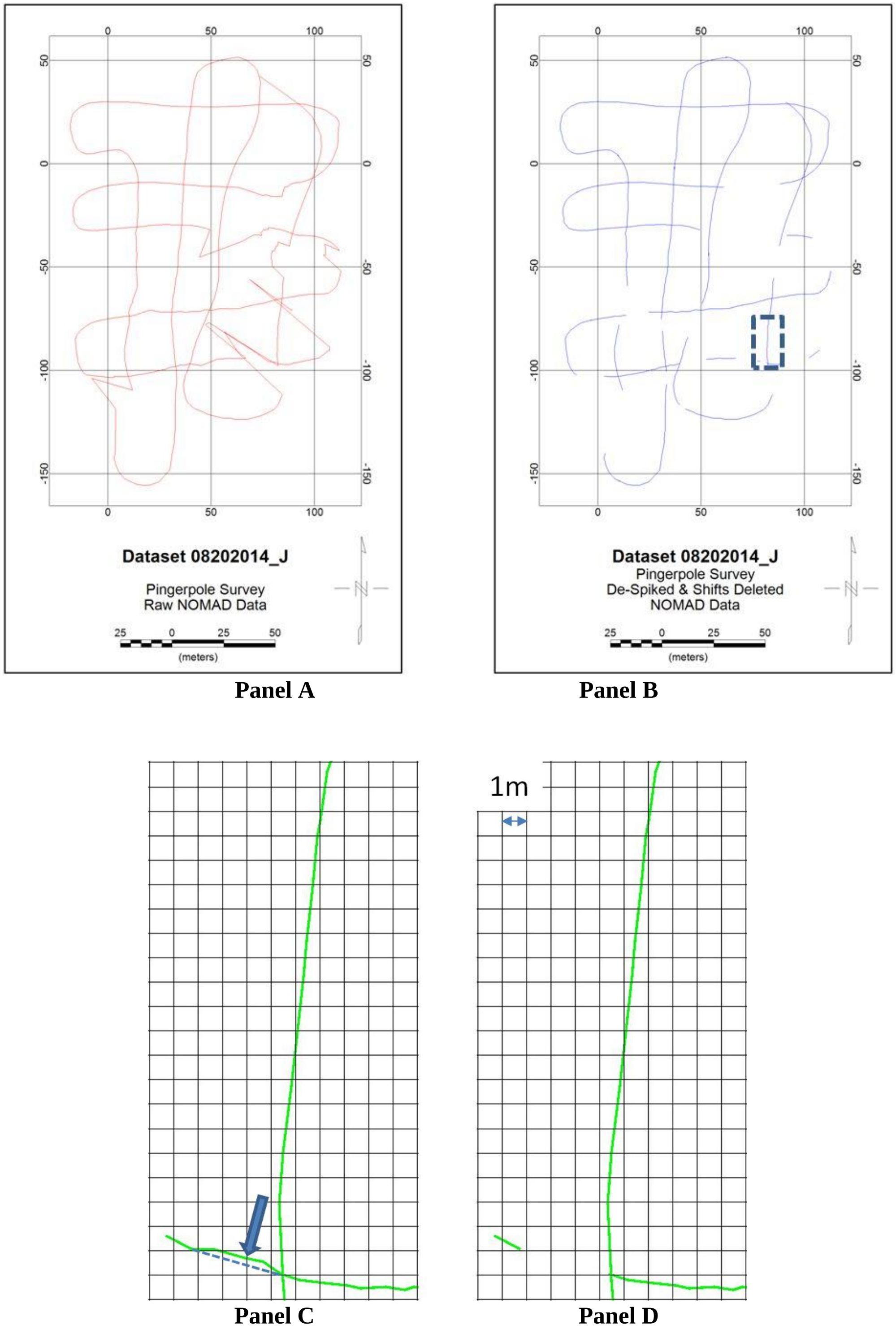


Figure 21: Panel A shows raw NOMAD data. Panel B shows the data with large spikes removed. Also in this panel is a dashed-line rectangle highlighting the area enlarged in Panels C & D. Panel C shows raw NOMAD data with an atypical shift of ~50 cm in the track of the pinger. Panel D shows the track-plot with all errors removed.

6.1.4 ROTATE AND TRANSLATE THE NOMAD DATA INTO THE UTM ZONE 15N COORDINATE SYSTEM

The coordinate warp tool in Oasis Montaj was used to rotate and translate NOMAD data in to UTM Zone 15N coordinates. This is achieved by identifying four known locations common to both datasets as described in Section 5.1. The points where east-west lines cross north-south lines are common to both datasets and are used to accomplish the rotation and translation task. Once the NOMAD and GPS datasets are in the same coordinate system, they can be superimposed as in Figures 22 through 25 for the four pinger pole surveys performed.

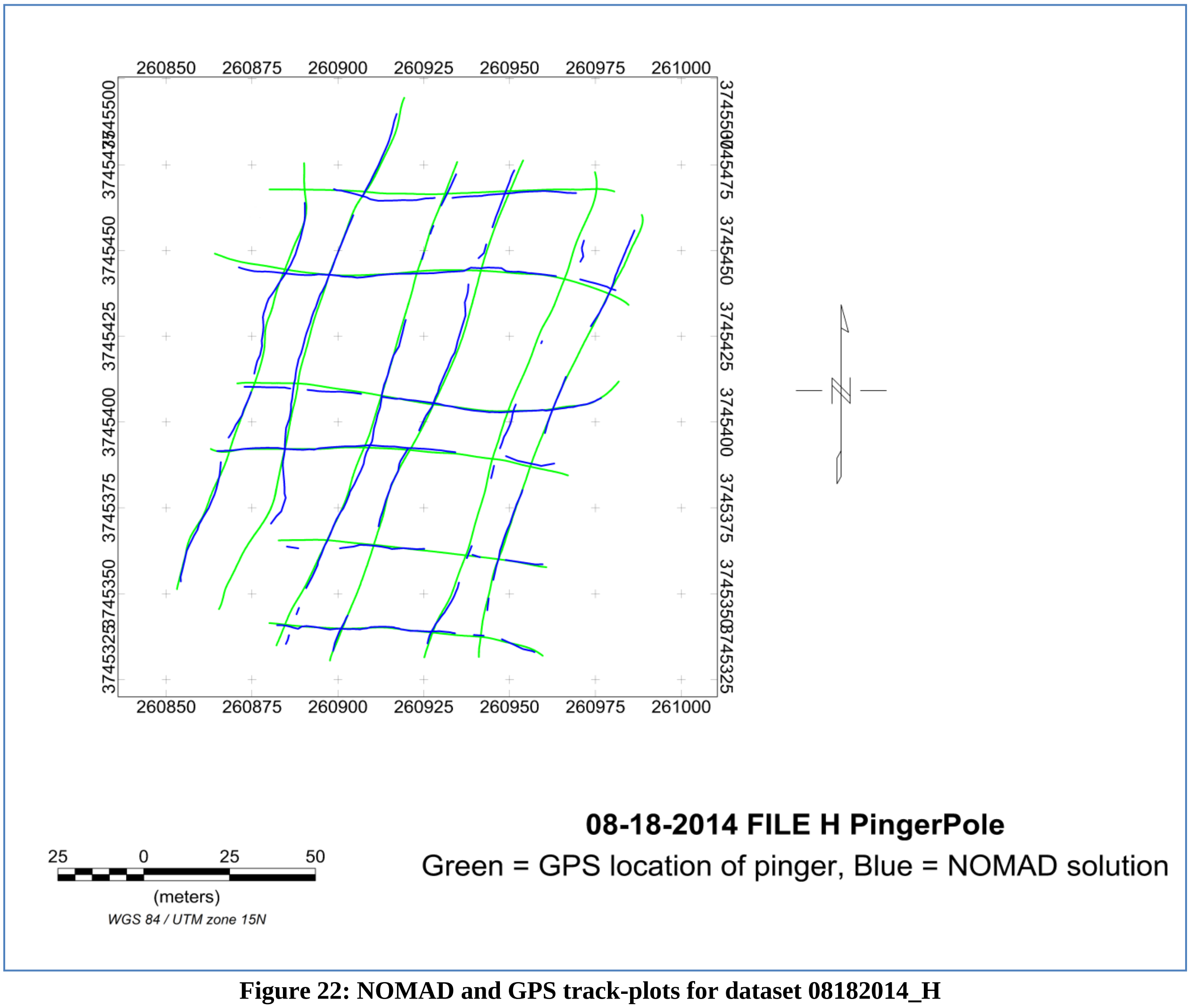


Figure 22: NOMAD and GPS track-plots for dataset 08182014_H

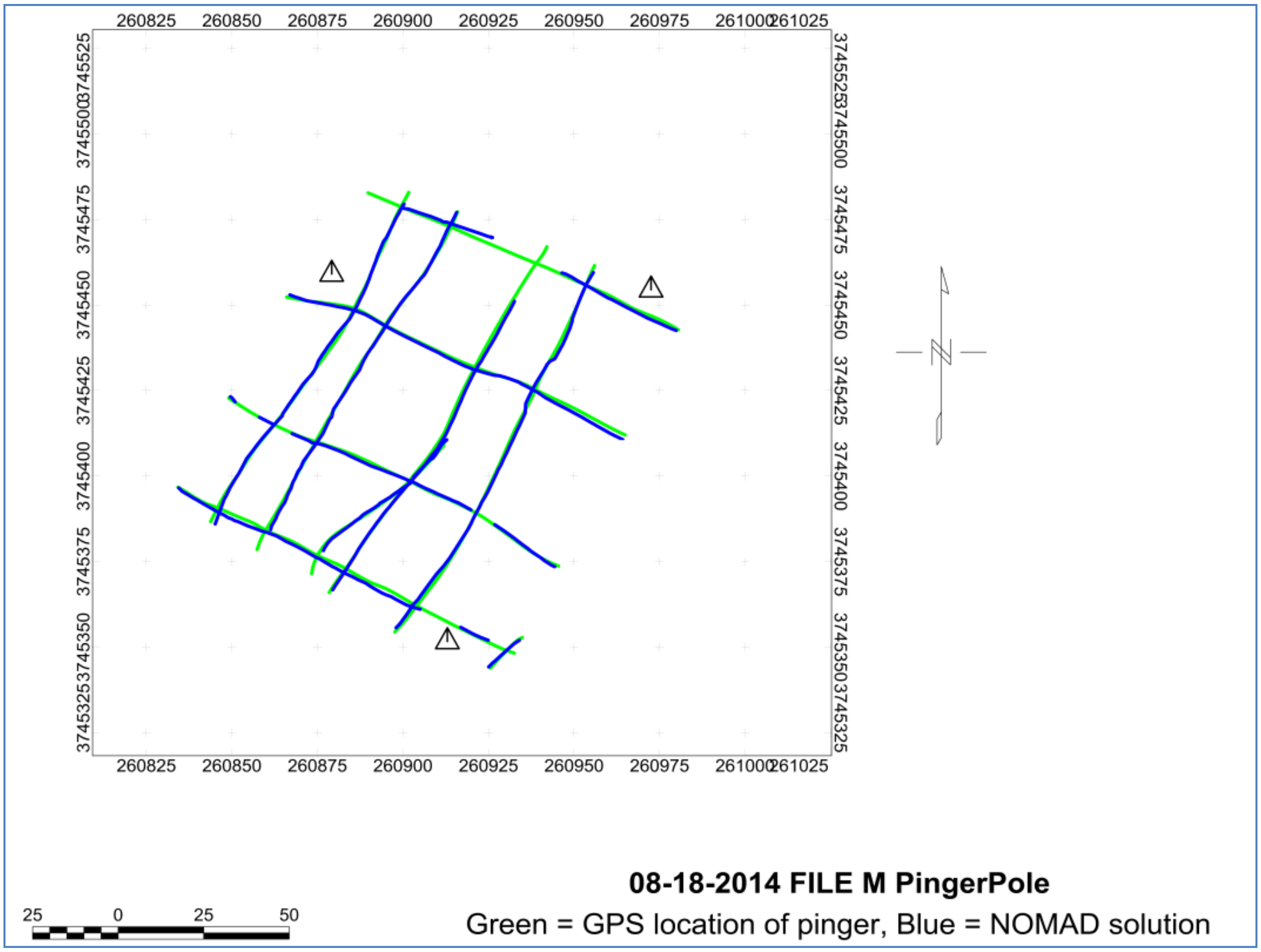


Figure 23: NOMAD and GPS track-plots for dataset 08182014_M

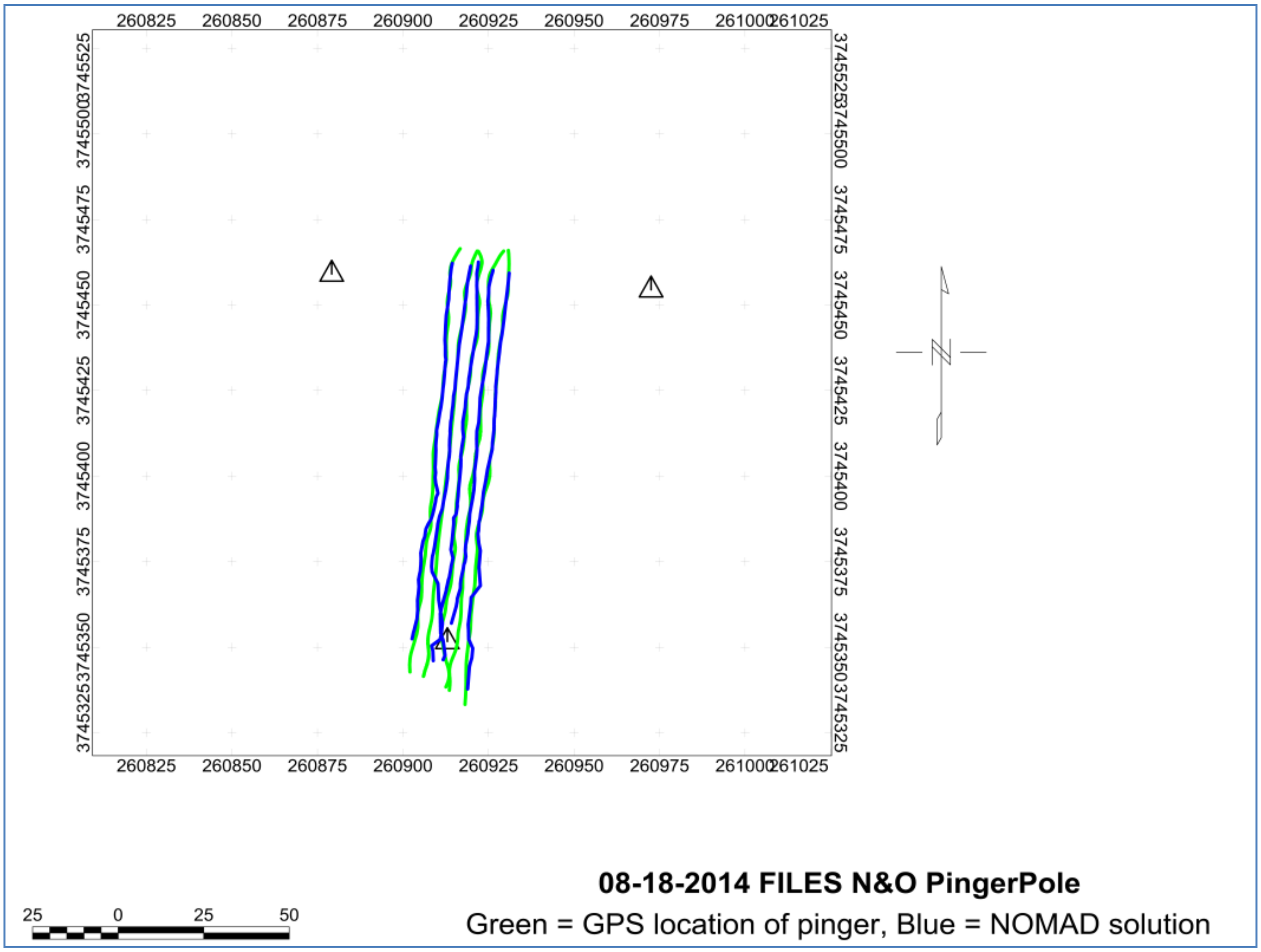


Figure 24: NOMAD and GPS track-plots for dataset 08182014_N&O

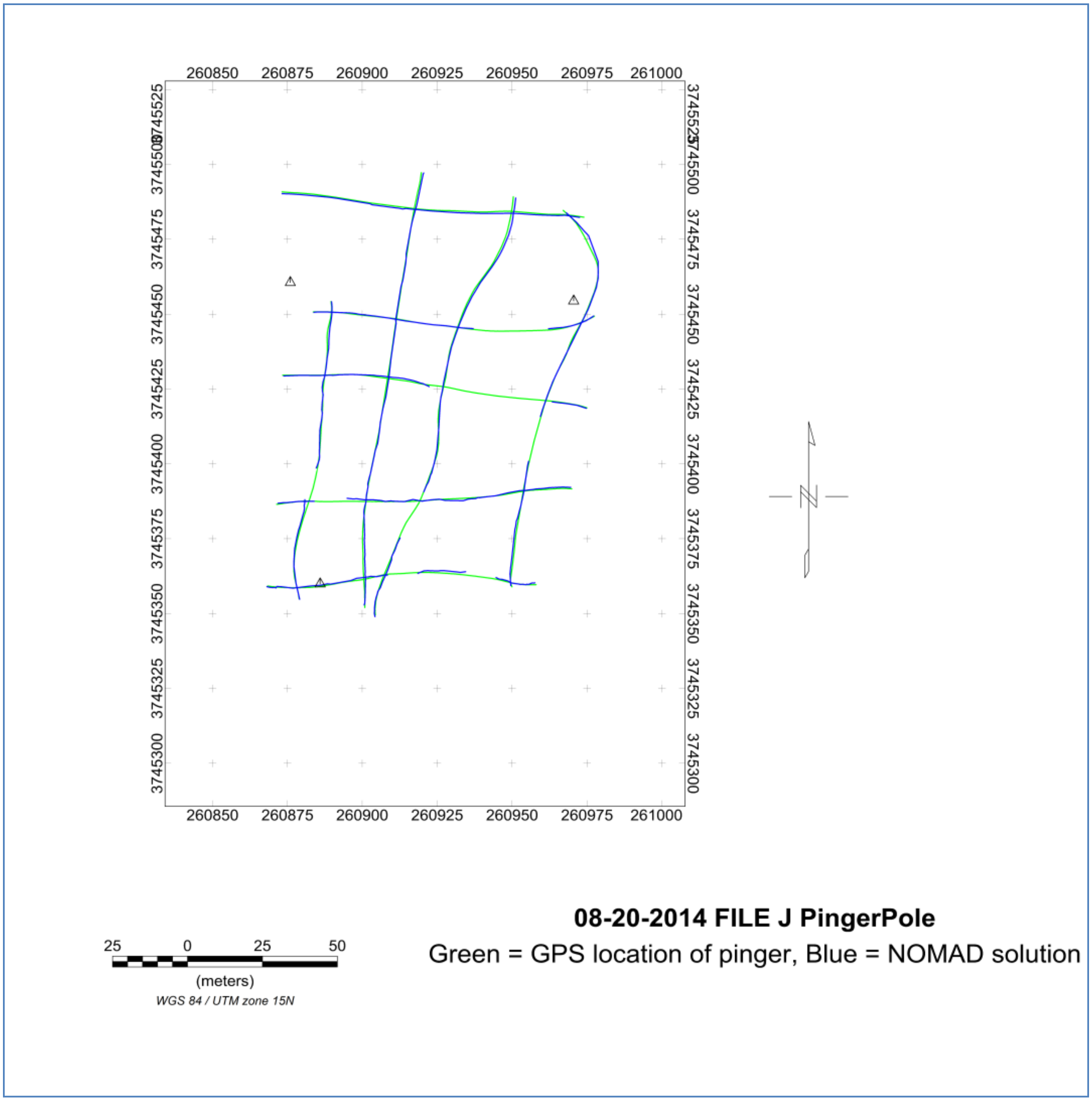


Figure 25: NOMAD and GPS track-plots for dataset 08202014_J

6.1.5 CALCULATE THE SHORTEST DISTANCE FROM EACH NOMAD POINT TO THE LINE CREATED BY THE TWO NEAREST GPS LOCATIONS

The shortest distance from each NOMAD point to the RTK-DGPS track-plot was calculated using the process described below. This process makes use of the 10 Hz sampling rate used in the GPS system, which equates to RTK-DGPS points measured about every 10 cm along-track.

1. Identify the RTK-DGPS data point nearest to each NOMAD point

2. Identify the RTK-DGPS data points immediately preceding and following the nearest point
3. Determine which side of the nearest RTK-DGPS point the NOMAD point is located
4. Calculate the perpendicular distance between the NOMAD point and the line between the nearest point (from step #1) and the RTK-DGPS point from step 3.

Steps 1 and 2 were performed as database searches. Step three was performed as a simple least-distance test between the NOMAD point and the two RTK-DGPS points from step 2. Step 4 was performed using simple geometry.

6.1.6 CALCULATE STATISTICS ON DISTANCES BETWEEN NOMAD POINTS AND ACTUAL TRACK-PLOT

The average, maximum, minimum and standard deviation of the distances calculated in step 5 are presented in Table 8. Note that these statistics include the estimated 15cm error attributed to the tilt measurement of the pinger pole while under-way.

Table 8: Pinger pole Comparison Statistics

Dataset ID	Number of Points	Minimum (m)	Maximum (m)	Average (m)	Standard Deviation (m)
08182014_H	669	0	3.2	0.67	0.59
08182014_M	560	0	2.04	0.49	0.39
08182014_N&O	323	0	4.01	0.49	0.53
08202014_J	595	0	1.38	0.3	0.24

Histograms of the distances calculated in step 5 are presented in Figures 26 through 29. For all figures the vertical axis is the frequency of occurrences, the horizontal axis is in units of meters.

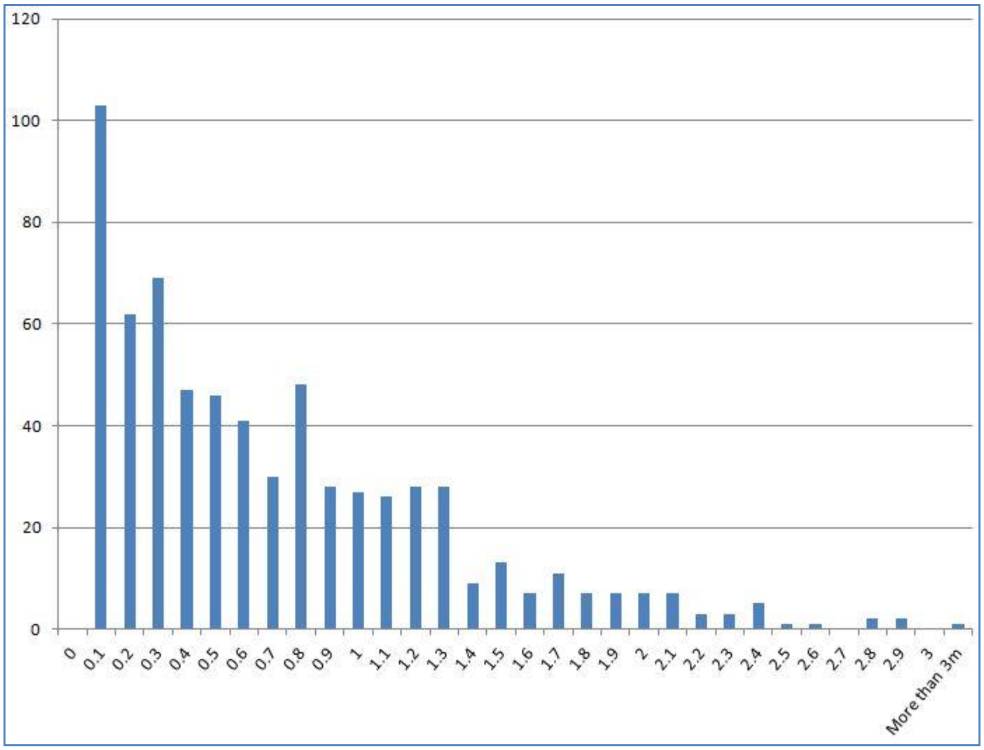


Figure 26: Distance histogram for dataset 08182014_H.

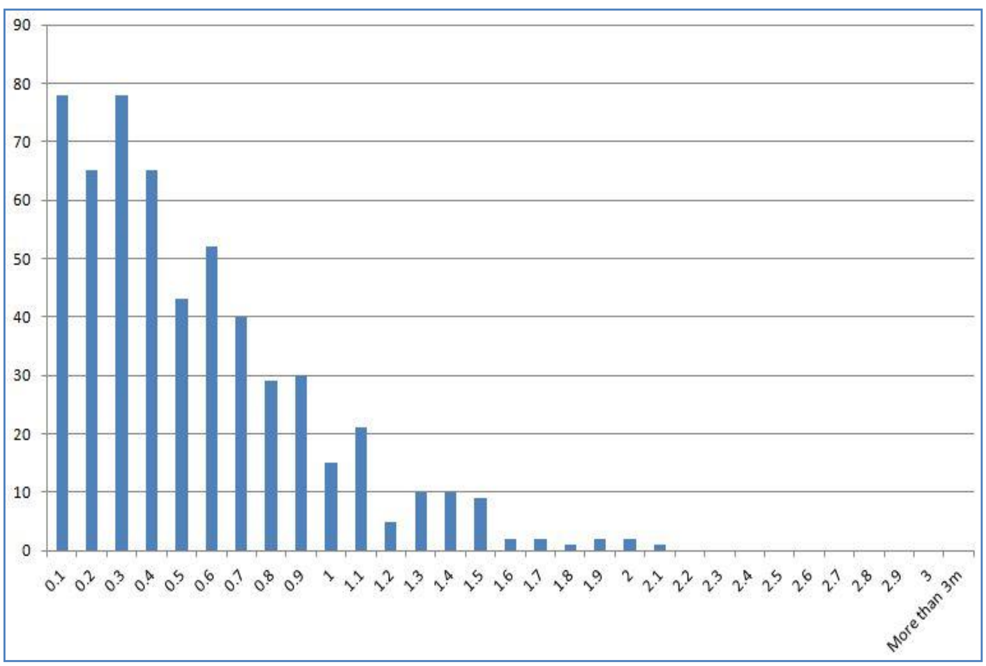


Figure 27: Histogram of distances between NOMAD and GPS positions for dataset 08182014_M

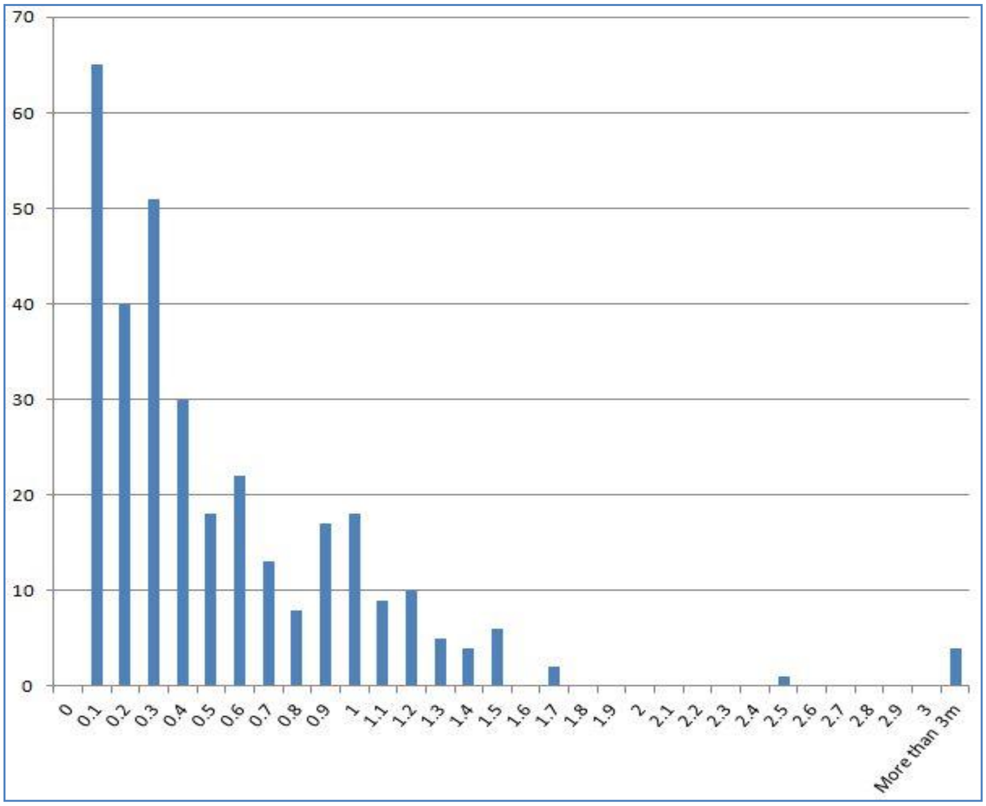


Figure 28: Histogram of distances between NOMAD and GPS positions for dataset 08182014_N&O

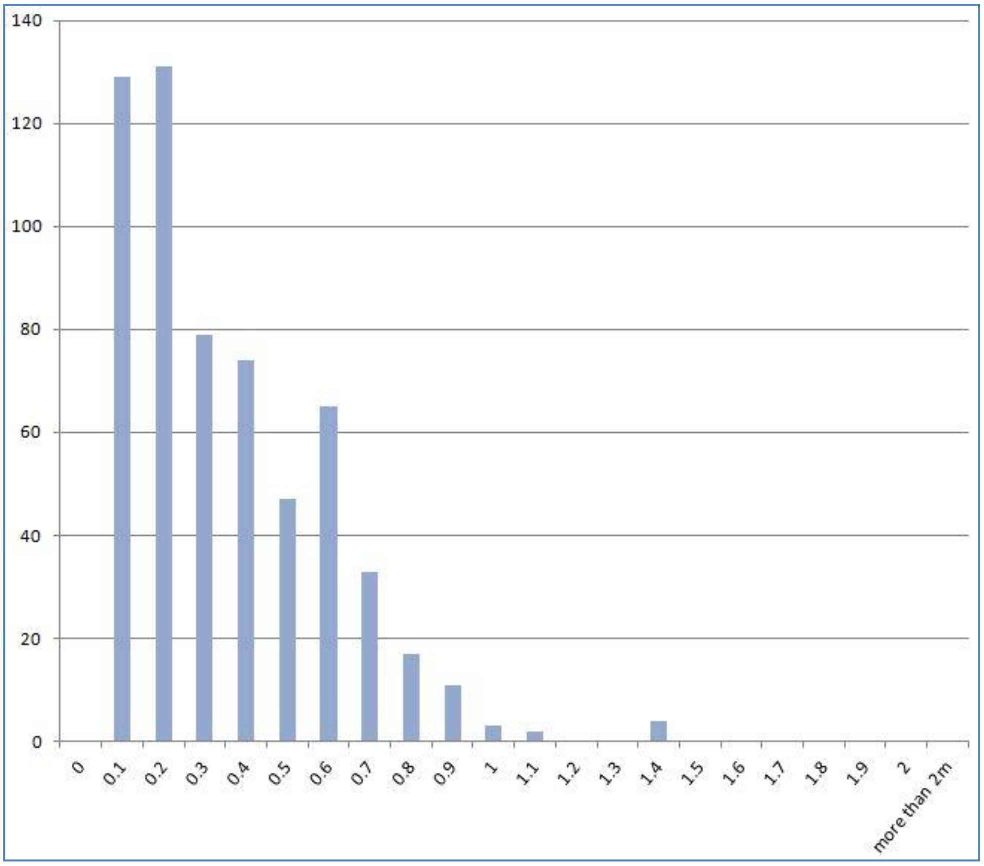


Figure 29: Histogram of distances between NOMAD and GPS positions for dataset 08202014_J

6.2 MAGNETOMETER DATA ANALYSIS

Each of the three magnetometer datasets were processed and analyzed using the following steps:

1- Merge the magnetometer and NOMAD data using the MagMap2000 software
2- Delete spikes in the NOMAD track-plot
3- Interpolate NOMAD positions for each magnetometer position assuming a straight line between NOMAD points
4- Calculate magnetometer sensor positions from the NOMAD positions using Geosoft's Sensor Offset Correction routine
5- Provide a correction factor to the magnetometer positions to account for the 4.5 to 6 second lag in the NOMAD data stream using Geosoft's Lag Correction routine
6- Rotate and translate the NOMAD coordinates to real-world coordinates using Geosoft's Warp Dataset routine
7- Filter the magnetometer data to remove diurnal effects (low frequency) and system noise (very high frequency). This step reduces background measurements to a zero baseline, precluding the need for base station corrections.
8- Calculate analytic signal grid maps of the magnetometer data
9- Identify anomalies common to the three magnetometer data sets and calculate distances between each
10- Calculate average and standard deviation of the distances calculated in step 9.

Step 1 was performed using standard MagMap2000 software. Step 2 was performed in the same manner described for the pinger pole surveys in Section 6.1.2 above. Steps 3 through 8 were performed using routine Geosoft data analysis tools. As noted previously in this report, a variable lag exists in the time the NOMAD software receives ping data from the bottom stations and the time that ping's position solution is broadcast over the RS232 communications port to the MagLogNT software. There is no method to assess when the lag changes, nor is it known what caused it or how it behaved. Incremental lag corrections were applied to each dataset individually until the chevron effects in the data were minimized.

Nine anomalies were identified that are common to all three datasets, and three additional anomalies that are common the datasets 08192014_C and 08202014_E. Figures 30 through 32 show the total field magnetometer results with the track-plots of the acquired data. Figures 33 through 35 show the analytic signal results with anomalies used for the statistics calculations identified. Table 9 presents the distances between identical anomalies in the three datasets, along with the average and standard deviation of all distances in the table.

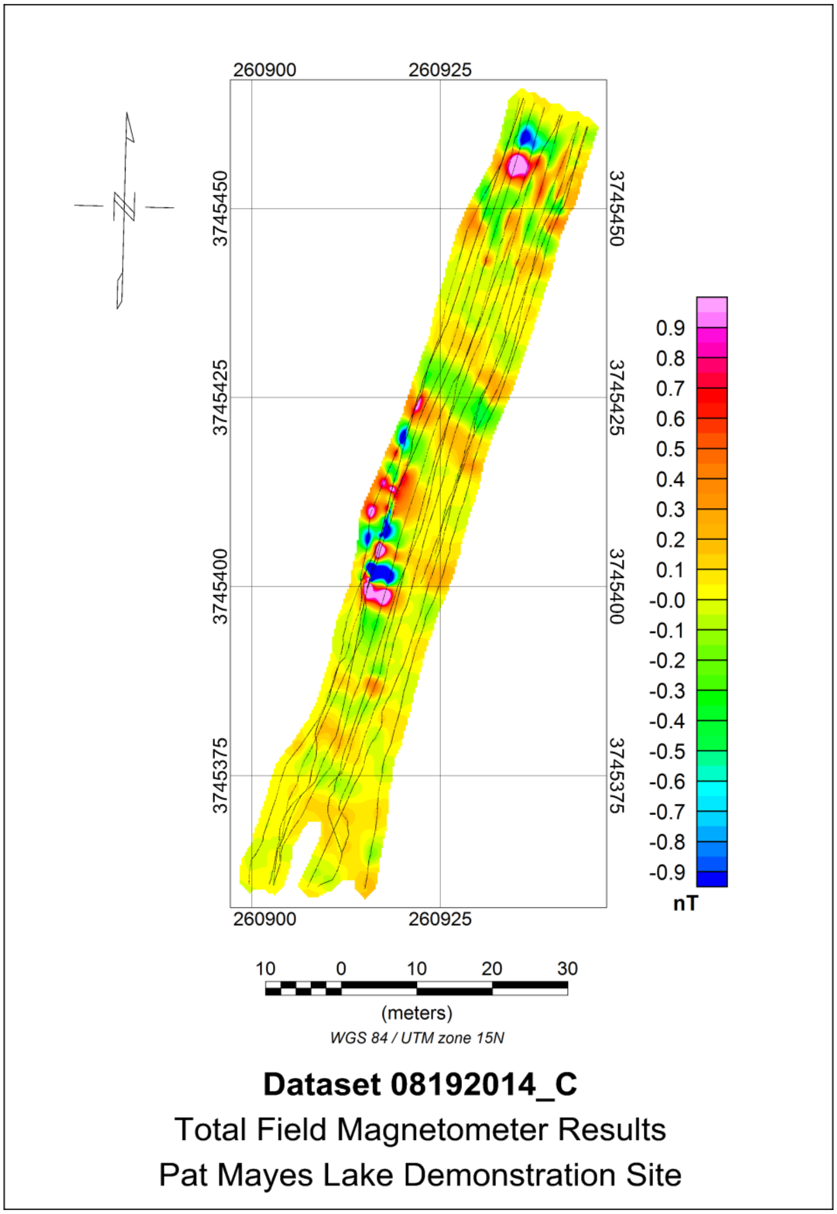


Figure 30: Magnetometer total field results for dataset 08192014_C

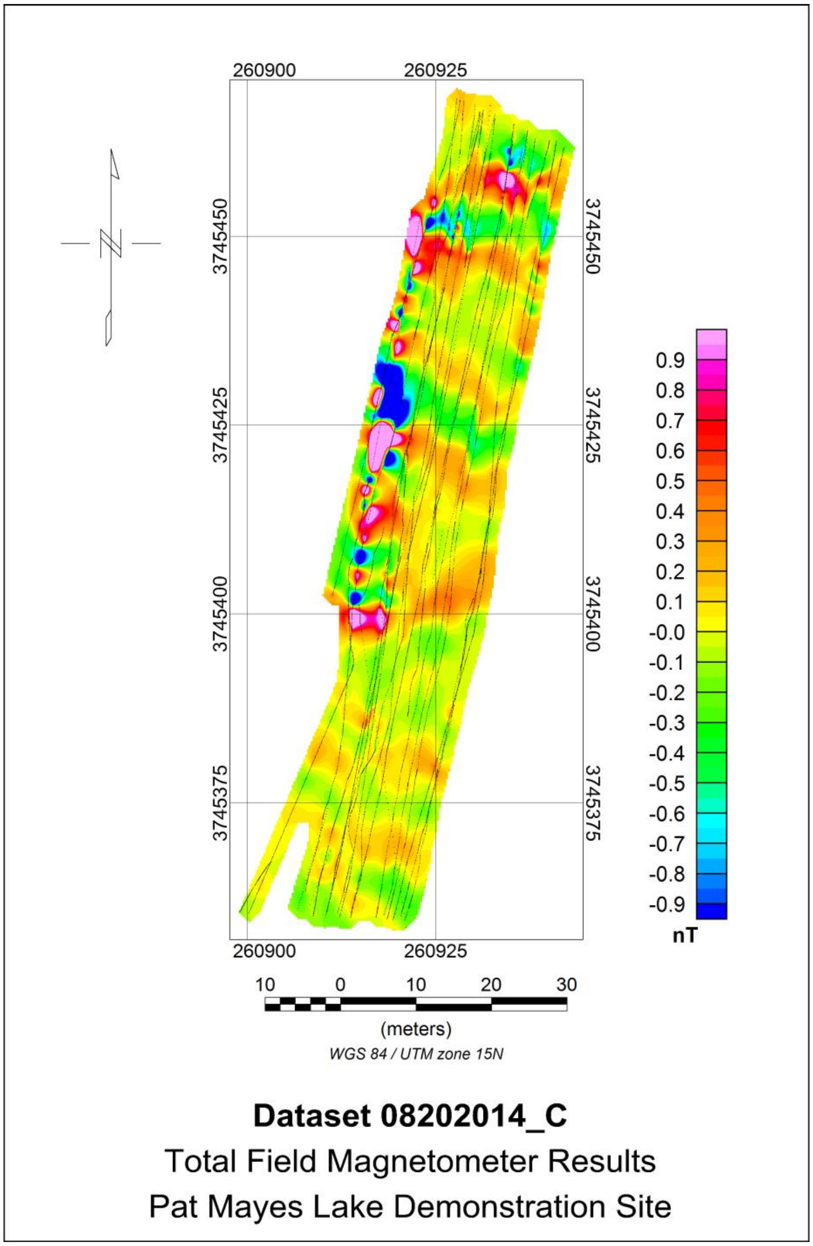


Figure 31: Magnetometer total field results for dataset 08202014_C

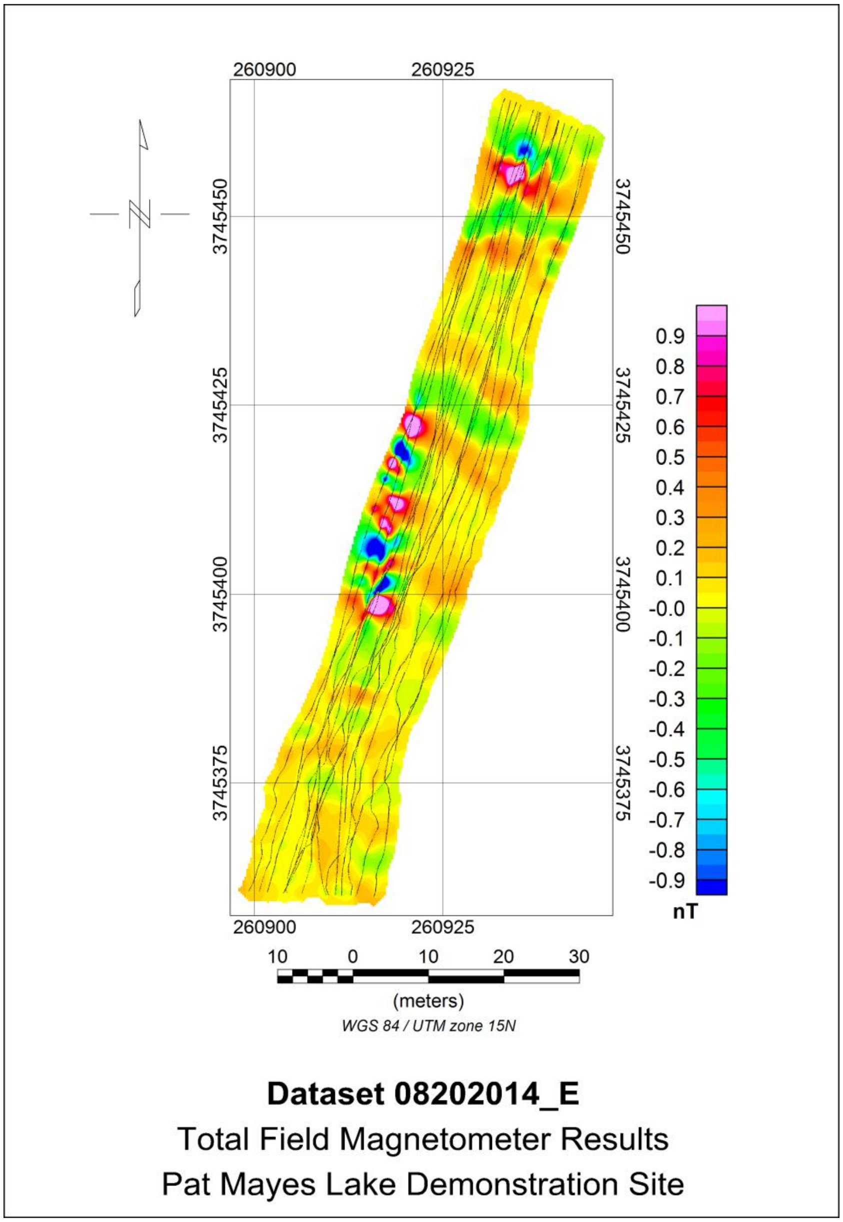
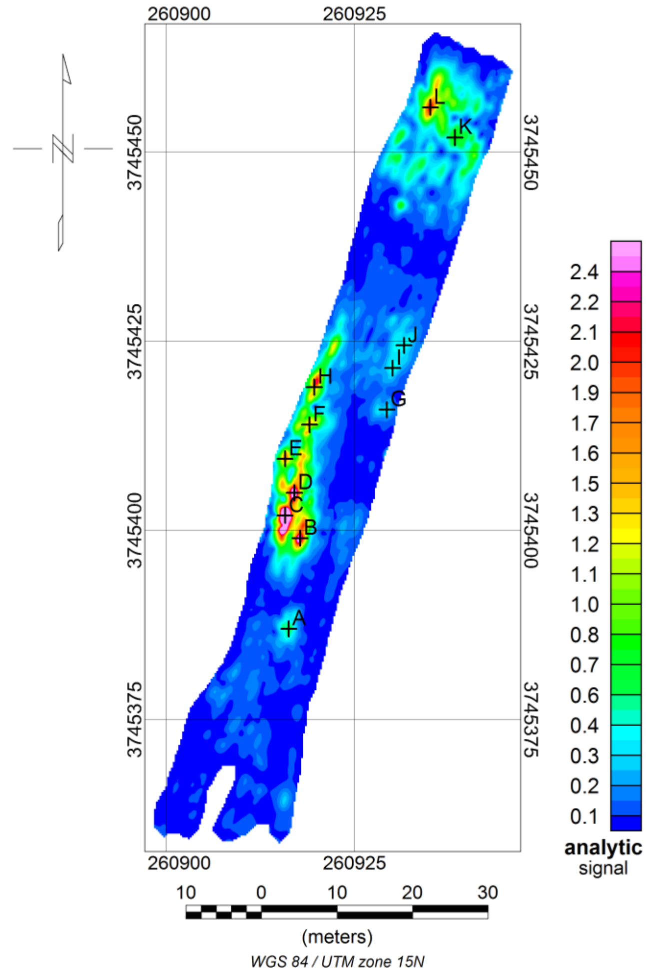


Figure 32: Magnetometer total field results for dataset 08202014_E



Dataset 08192014_C

Analytic Signal Magnetometer Results

Pat Mayes Lake Demonstration Site

Figure 33: Analytic signal results for dataset 08192014_C

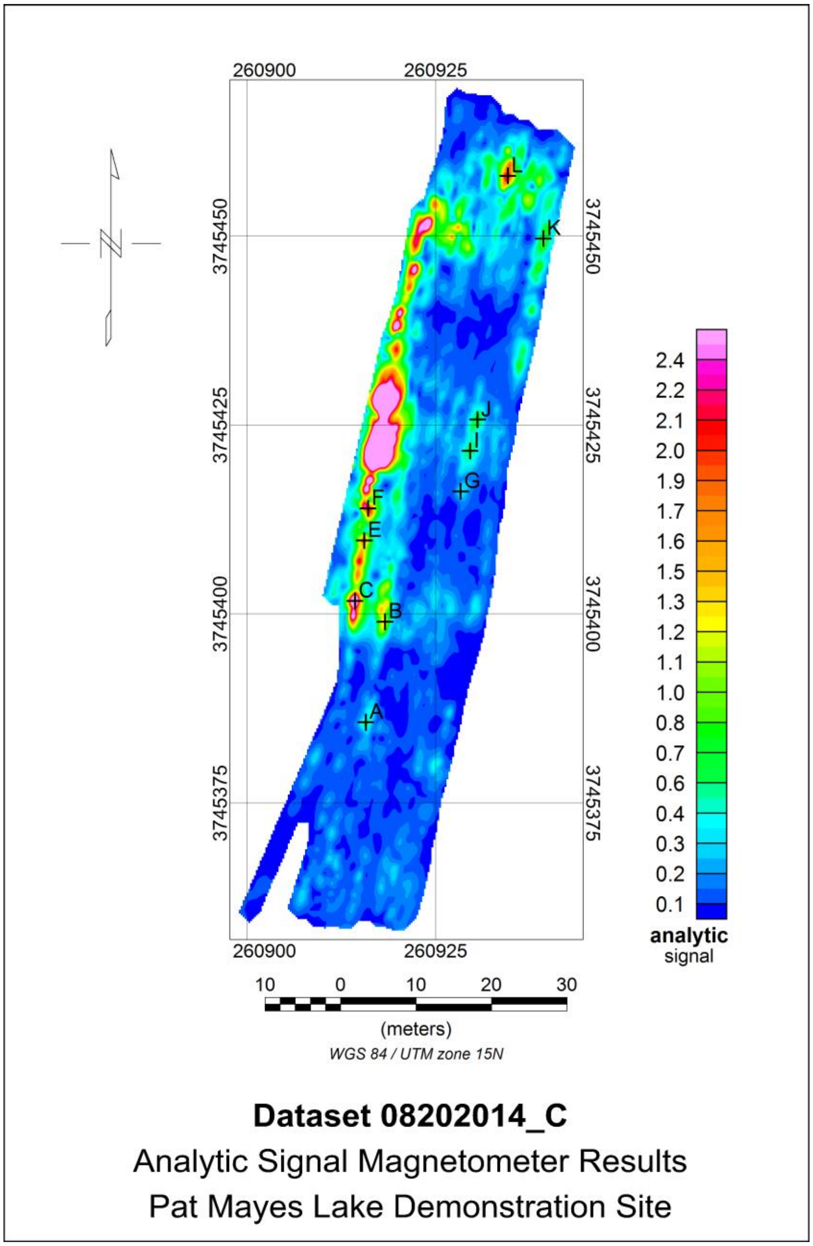


Figure 34: Analytic signal results for dataset 08202014_C

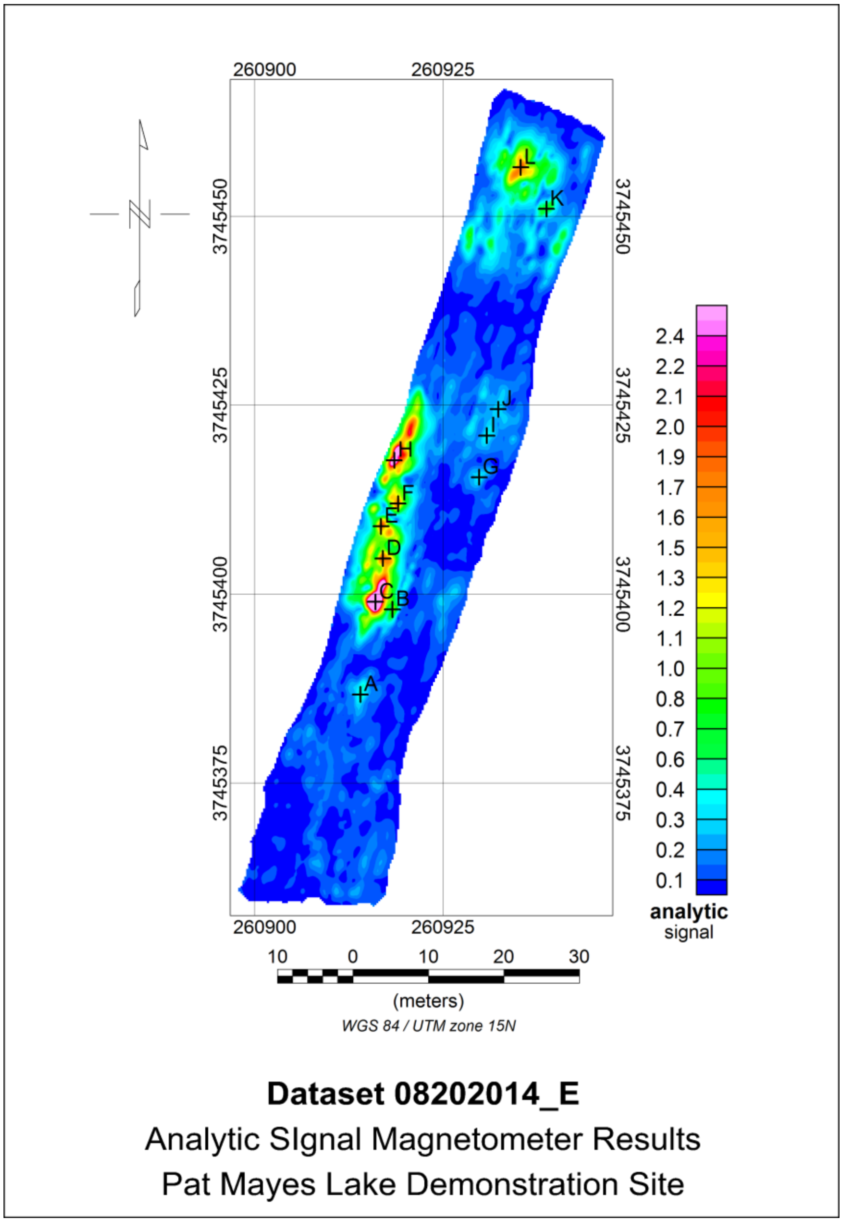


Figure 35: Analytic signal results for dataset 08202014_E

Table 9: **Distances Between The Same Sources In Three Independent Magnetometer Surveys**

Line targets_08192014_C			Line targets_08202014_C			Line targets_08202014_E			Distance Between Datasets (meters):		
Easting (meters)	Northing (meters)	ID	Easting (meters)	Northing (meters)	ID	Easting (meters)	Northing (meters)	ID	19C & 20C	19C & 20E	20C & 20E
260916.3	3745387.0	A	260915.7	3745385.7	A	260914.0	3745386.8	A	1.4	2.3	2.0
260917.8	3745399.0	B	260918.3	3745399.0	B	260918.3	3745398.0	B	0.5	1.1	1.0
260915.8	3745402.0	C	260914.3	3745401.8	C	260916.0	3745399.0	C	1.5	3.0	3.3
260917.0	3745405.0	D	could not	interpret		260917.0	3745404.8	D		0.2	
260915.8	3745409.5	E	260915.5	3745409.8	E	260916.8	3745409.0	E	0.4	1.1	1.5
260919.0	3745414.0	F	260916.0	3745414.0	F	260919.0	3745412.0	F	3.0	2.0	3.6
260929.3	3745416.0	G	260928.3	3745416.3	G	260929.8	3745415.5	G	1.0	0.7	1.7
260919.6	3745419.0	H	could not	interpret		260918.5	3745417.8	H		1.6	
260930.0	3745421.5	I	260929.5	3745421.6	I	260930.8	3745421.0	I	0.5	0.9	1.4
260931.5	3745424.5	J	260930.5	3745425.8	J	260932.3	3745424.5	J	1.6	0.8	2.2
260938.3	3745452.0	K	260939.2	3745449.7	K	260938.6	3745451.0	K	2.5	1.0	1.4
260935.0	3745456.0	L	260934.5	3745458.0	L	260935.3	3745456.5	L	2.1	0.6	1.7
								Average:		1.6	
								Standard Deviation:		0.9	

7.0 PERFORMANCE ASSESSMENT

Table 10: Performance Metrics

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Seed Item Location Accuracy	Average and standard deviation in the difference between seed item location and: a) interpreted anomaly location, and b) indicated location upon reacquisition	Detection list of seed items (detection locations compared to actual)	Δ Position offsets ≤ 0.65 m
		Reacquisition coordinates of seeded items (reacquired locations compared to actual)	Δ Position offsets ≤ 0.95 m
		Reported locations of Reacquired seed items (NOMAD reported compared to actual)	Δ Position offsets ≤ 0.35 m
			σ Position offsets ≤ 0.15 m
Pinger pole Position Accuracy	Average and standard deviation in the difference between each NOMAD pinger pole position and the track of the RTK-DGPS positions of the pole	List of the shortest distance between each useable NOMAD pinger pole solution and the track of the pinger pole as recorded by the RTK-DPGS	Δ Position offsets ≤ 0.35 m σ Position offsets ≤ 0.15 m
NOMAD setup time	Time required to deploy and calibrate 4 NOMAD baseline stations	• Log of system deployment times accurate to 15 minutes	NOMAD setup time: < 45 minutes
Qualitative Performance Objectives			
Quality of dipole signatures	Cleanliness of dipole signatures	Pseudo color map of measured total field magnetometer data.	Dipole signatures exhibit regular, single-source characteristics.
Ease of use	Setup, deployment, operations and retrieval of the hardware, and merging the positioning data with the mag data	• Feedback from user(s) on usability of technology and time required	Feedback from field personnel indicates minor improvements, or no improvements are needed.

Three quantitative and two qualitative metrics were established for this demonstration: seed item location accuracy, pinger pole position accuracy, setup time, quality of dipole signatures and ease of use. Each of these is discussed below.

7.1 SEED ITEM LOCATION ACCURACY (QUANTITATIVE)

The metric for this objective is a mean of 0.65 m with standard deviation of 0.15 m or less. This metric was not achieved; the mean reproducibility of detected anomalies in three independent magnetometer surveys was 1.6 m with standard deviation 0.9 m. The results of detected anomaly reproducibility are summarized in Table 9.

This objective was assessed by comparing the reproducibility of the locations of ten unique anomalies common to all three datasets and two unique anomalies common to two datasets. The intended method of assessing this metric using known seed item locations could not be performed because seed locations could not be established as planned. Section 3.1 of this report explains why.

Three factors are believed to have contributed the degraded anomaly location reproducibility performance compared to the significantly better performance measured in pinger pole position accuracies (see Section 7.2 below). First, the variable 4.5 to 6 second lag in position fixes received at the MagLogNT computer is believed to be the primary cause. The source and behavior of this lag is unknown, but may be partially attributed to the computing power of the computer running the NOMAD software, which was a Toshiba Portégé model R835-P89. Point-to-point accuracies should not be greatly affected by variable lag. However, at the approximate 4.5 knot speeds travelled during the demonstration, a quarter second lag change between lines would result in almost 0.6m change in position, which is significant in terms of positioning geophysical data.

The second factor is that a range hole was present in the general vicinity of the target field, and fixes did not update at the programmed 1 Hz update rate. Position gaps were interpolated assuming straight lines were followed between position fixes. The range hole was likely due to increased reverberation caused by bottom topography and NOMAD geometry, though it may be other factors such as a thermocline or the signal from one or more bottom stations being shadowed by the towfish or some other bottom obstruction.

The last factor is inconsistent towfish depth below the surface, which is not associated with NOMAD. Different towfish depths were observed in the real-time MagLogNT interface, and were caused by differing tow speeds. Every effort was made to keep the tow speeds constant but this proved difficult due to the direction of travel (either in to, or with the wind), and difficulties in maintaining similar engine speeds from line to line. Differences of up to 40 cm were noted at various times during the surveys. Differences in towfish height from line to line contribute to difficulties in reproducing clean dipole signatures, which in turn complicates interpretations and localizing magnetic anomaly sources.

7.2 PINGER POLE POSITION ACCURACY (QUANTITATIVE)

The metric for this objective is a mean of 0.65 m with standard deviation of 0.15 m or less. This metric was achieved in the last test; the mean reproducibility of the actual pinger locations, as recorded by the RTK-DGPS, ranged from 0.3 (last test) to 0.67 m (first test) and the standard deviations ranged from 0.24 (last test) to 0.59 m (first test). Though the standard deviations never went below 0.24 m, the metric is considered achieved for the last test because 99% of the NOMAD solutions were within 1.02 m of their actual locations, compared to the initial metric requiring 99% to be within 1.1 m. Table 11 presents this information. The results of the pinger pole tests are summarized in Table 8 and the histogram plots in Figures 26 through 29.

Table 11: Pinger pole Position Accuracy Summary

Dataset	Metric Upper Bound @ 95th percentile	Metric Upper Bound @ 99th percentile	Mean Difference Between Positions	Standard Deviation Between Positions	Accuracy Upper Bound @ 95th percentile	Accuracy Upper Bound @ 99th percentile
08182014_H	0.95 m	1.1 m	0.67 m	0.59 m	1.87 m	2.44 m
08182014_M	0.95 m	1.1 m	0.49 m	0.39 m	1.27 m	1.66 m
08182014_NO	0.95 m	1.1 m	0.49 m	0.53 m	1.55 m	2.08 m
08202014_J	0.95 m	1.1 m	0.30 m	0.24 m	0.78 m	1.02 m

The manual calibration tasks (described in Section 5.4) that improved system performance were learned in the time between the first test (data file 08182014_H) and last test (data file 08202014_J). Those improvements are attributed to the increase in performance.

7.3 NOMAD SETUP TIME (QUANTITATIVE)

The metric for system setup time was 45 minutes. This objective is considered achieved. The average setup time reported in Section 3 was 47 minutes, which does not account for errors in reported times; the operator would sometimes log the end time for various tasks several minutes after their actual completion. In addition, most of the manual steps described in Section 5.4 could easily be automated in the software, which if implemented in future versions will significantly reduce the setup time.

7.4 QUAILTY OF DIPOLE SIGNATURES (QUALITATIVE)

The metric was for the dipole signatures to exhibit regular, single-source characteristics. This metric was achieved in most portions of the 08192014_C and 08202014_E datasets (Figures 30 and 32, respectively), and in some portions of the 08202014_C dataset (Figure 31). The higher data quality observed in dataset 08192014_C is likely due to calmer wind conditions, which facilitated keeping constant vessel speed, which in turn should have resulted in more constant towfish altitudes throughout the survey. In contrast, increased wind the following day is attributed to the decrease is data quality for dataset 08202014_C where lines were collected sequentially rather than in a Zamboni pattern. The Zamboni pattern used for the majority of dataset 08202014_E is attributed with the increase in data quality compared to 08202014_C.

Though the anomaly locations vary, on average, by 1.6 m between datasets, the reproducibility of the magnetic fields is considered good. This is supported by the repeated background signatures observed throughout the data, as well as with several of the larger amplitude anomalies attributed to some of the seeds and pre-existing sources. This reproducibility of the magnetic field but lack of repeatability in actual locations between the datasets is unexplained at this time. It likely is due, at least in some part, to the variable latency problem. However it is not likely that the latency problem is the sole cause since there is both an along-track and across-track difference in locations. The cause is not believed to be due to the coordinate transforms used as they are the same as those used for the pinger pole tests, which were much more successful. Additional tests using a target field with known seed locations would help assess the error observed in this test.

7.5 EASE OF USE (QUALITATIVE)

The metric for the ease of use was for personnel feedback to indicate only minor improvements, or no improvements needed for the system. This metric is considered achieved. Hardware setup, deployment and retrieval are simple, quick, and easy. The software is simple to use, though it would benefit greatly from the improvements described in Section 3.5. Contributing to the software's ease of use are the existing automated functions for setting thresholds and performing baseline surveys to automatically establish the local bottom station network. In additions, it does not require constant attention. An added benefit would be automating the pinger pole survey to calculate real-world coordinates for the bottom stations in real-time. Of significant concern is the variable latency issue, which does not affect ease of use per-se, but does complicate geophysical data analysis.

Table 12 summarizes the ease of use of the system and identifies areas for improvements

Table 12: NOMAD Ease of Use Summary

Item	Comments	Recommendations
Hardware setup is simple	Setup time for all four bottom stations is less than an hour. Parts go together easily.	None
Hardware deployment is easy	The buoys and bottom stations are easily deployed by one or two people	None
Hardware retrieval is easy	1. The RFRs are easily retrieved for charging while not moving the bottom stations 2. The buoys and bottom stations are easily retrieved by one or two people	Ease of use would be greatly improved if a lighter-weight electro-mechanical cable were used to connect the RFRs to the bottom stations and in particular the asset (rover) pinger.

Battery life	The RFRs last at least an entire 12 hour survey day	None
Hardware durability	Most components are robust. No breakage occurred during the tests. The RFR antenna is the weakest item	Use rugged RFR antennas.
Software Interface	Easy to understand. GUIs are uncluttered and functional.	None
Software usability	Easy to install and use. A little annoying having to switch between calibration software and normal operations software.	Package everything needed to run NOMAD in a single software package
Software robustness	Satisfactory. There were many instances when the system would hang-up and crash. Suspect this is due to a software bug.	Fix bug(s) that cause the software to crash.
Software Functionality	Generally good. Areas for improvement include those from Section 3.5 (reproduced below) as well as automating the pinger pole survey and reducing system latency. 1. Temperature compensation of the depth sensor is not functional. 2. Manual depth entries of the bottom stations during calibration are required 3. Manual calculation of the average location of bottom stations is required 4. Manual input of asset(rover) pinger depth is required	1. Automate the pinger pole survey to calculate bottom station world coordinates in real-time 2. Automate the manual tasks listed in items 1 through 4 at left. 3. Identify & correct the cause of the variable latency
To-Be-Considered	The pinger pole survey could be simplified by automating tilt compensation corrections	Integrate a real-time IMU (Inertial Measurement Unit) to the pinger pole survey

8.0 COST ASSESSMENT

The cost of a NOMAD system with four bottom stations and one asset (rover) pinger is $86,000. For a system identical to that tested, which includes having to perform the manual tasks described in Section 5.4, the hardware setup time is less than 1 hour for a crew of three, about an hour to install hardware on the survey vessel, and another 45 minutes to deploy and calibrate the system.

Other costs incurred include the survey vessel, which cost $3,500/day (including captain), the pinger pole and pinger pole mount. The pinger pole and mount were fabricated in-house. Their cost were not tracked, but are estimated at between $1,500 and $2,000 for one to two days metal-shop labor and raw materials. Other costs not incurred during the demonstration but would be required for normal operations, include RTK-DGPS rental at approximately $300/day and IMU purchase at approximately $2,000. Last, a dedicated water-resistant laptop would cost approximately $2,000.

8.1 COST MODEL

Tabulated below are the relevant cost factors for a NOMAD system.

Table 13: NOMAD Cost Model

Cost Element	Data Tracked During Demonstration	Estimated Cost
NOMAD cost as tested	Cost provided by Desert Star	$86,000
Survey vessel (includes captain)	Actual cost for ERDC support	$3,500/day
Out of box setup (one-time cost per project)	Time spent for this task by a crew of three	Less than 1 hour
Install hardware on vessel (one-time cost per project)	Time spent for this task by a crew of one	Less than 1 hour
Deploy and calibrate NOMAD (per area surveyed)	Time spent deploying and calibrating system	45 minutes
Retrieve bottom stations (per area surveyed)	Time spent retrieving bottom stations	10 minutes
Data Fusion (only cost of merging NOMAD data to geophysical data. Excludes geophysical data interpretation)	Actual time spent removing spikes and ~50cm shifts for data file 08202014_C	40 minutes

8.2 COST DRIVERS

Cost drivers for the current system are the manual calibration routines, the bugs in the software that cause it to crash fairly frequently and that cause the variable latency issue, and the range of the pingers, which is about 100 to 125 m.

As discussed in the body of this report, automating the calibration routine established during this demonstration can easily be automated now that the needs are known. Correcting the bugs that

cause the GUI to crash during operations and correcting the variable latency problem and the intermittent ~50 cm shifts will greatly enhance system usability.

System range can only be improved by adding bottom stations to the network, which is simple to do and supported by the current version of the system. Operating any COTS acoustic positioning systems in very shallow water (3 to ~7) meters is always challenging due to reverberations and multipath issues. This is true for NOMAD as well. Operating the system in deeper water is expected to reduce the number of spikes.

8.3 COST BENEFIT

The advantage NOMAD has over currently available COTS LBL systems are low cost for a sub-meter positioning system, GPS clock synchronization for all acoustic assets, radio communication capability to each bottom station, and ease of bottom station deployment and baseline calibration. Comparable low-cost LBL systems (e.g. under ~$50K for LinkQuest PinPoint LBL) have sub-centimeter published accuracies, however the published information does not state if those accuracies are the pinger-to-pinger closures, which are the same as those achieved by NOMAD, or actual dynamic asset-pinger tracking capabilities. Higher cost systems (over $50K) have sub-decimeter published accuracies but are large and require larger vessels to deploy and retrieve. No other system is known to use GPS clock synchronization for the entire network of bottom stations and asset pinger, which greatly simplifies system design, programming, and maintenance.

A further benefit is the software's ease of use. Very little training was needed to install and operate the system.

9.0 IMPLEMENTATION ISSUES

The only implementation issues are those described in this report: improving the software robustness to preclude system crashes and solving the variable latency problem. Implementation can be greatly improved by automating temperature compensations to the depth measurements and integrating the depth measurements in to the baseline survey and the asset-tracking algorithm.

No Desert Star Systems personnel were on-site for the demonstration. Telephone support was not needed to learn any of the basic system controls or interfaces. Telephone support was required to debug some software issues, and two software updates were needed to complete the demonstration.

The NOMAD system is available for purchase from Desert Star Systems, LLC.

10.0 REFERENCES

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APPENDIX A: POINTS OF CONTACT

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